A Review on Flicker-Free AC–DC LED Drivers for Single-Phase and Three-Phase AC Power Grids

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***Abstract*—Light-emitting diodes (LEDs) are coming strongly into the lighting market due to their advantages over conventional lighting solutions: energy efficient, controllable in both light and color, long lifetime, lack of a warm-up period, and high power density. Some of these advantages will make LED light sources to be more than just a light bulb, being able to transmit data, control light color, hue, and intensity or even detect people in indoor environments. Nevertheless, these advantages attributed to LED capabilities are, in reality, achieved thanks to the LED driver. This paper reviews the current state-of-the-art strategies to drive LEDs from ac power grids with special emphasis into removing the most limiting component from the point of view of the lifetime, which is the electrolytic capacitor, while achieving a flicker-free performance of the light output of the LED driver. Moreover, it focuses on analyzing the required regulations, challenges, and applicability of LED drivers in both single-phase and three-phase ac power grids.**

***Index Terms*—AC–DC power conversion, capacitorless, flicker free, LED driver, power factor correction (PFC), single phase, three phase.**

I. Introduction

LIGHT-EMITTING diodes (LEDs) are becoming increasingly ubiquitous across all aspects of illumination products due to their reliability, long lifetime, energy efficiency, and low maintenance requirements. In fact, some of these advantages will make LED light sources to be more than just a light bulb, being able to transmit data [1]–[3], control light color, hue, and intensity or even detect people in indoor environments [4], [5]. Nevertheless, these advantages attributed to LED capabilities are, in reality, achieved by the LED driver, which can be defined as the power supply that controls and ensures an adequate light output of the LEDs.

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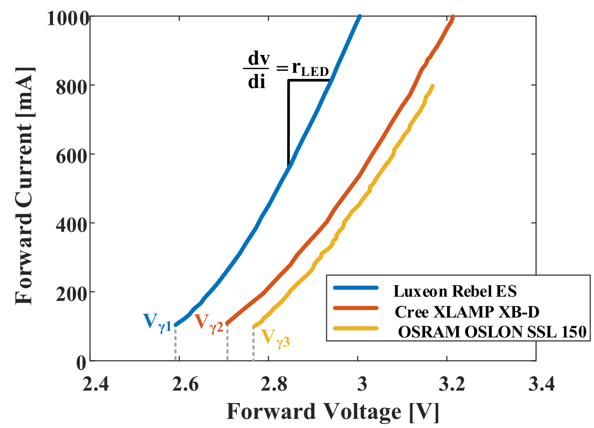


Fig. 1. *V–I* diagram for some commercial LED from the biggest manufacturers: Lumiled [9], Cree [10], and OSRAM [11].

In summary, the main electrical particularity of an LED is that significant current is only able to go across it in one direction, as any other diode. Hence, the LED can be considered as a nonlinear load that follows a *V–I* curve, as depicted in Fig. 1 for three different commercial LEDs. As can be seen, the curves are extremely similar to each other, and emphasis should be put at the higher knee-voltages (i.e., $V_{\gamma1}$, $V_{\gamma2}$, and $V_{\gamma3}$) when compared with traditional Schottky diodes. After reaching this value, the current rapidly increases causing the luminous flux to fluctuate accordingly, following an almost linear relationship [6], [7]. The aforementioned reasons imply that an LED load should be controlled in terms of its forward current instead of its forward voltage. Therefore, the luminous intensity of the light can be controlled online to be adequate to the requirements of the user; the online variation of this parameter in terms of a reference is referred in literature as dimming [8].

The main application for LEDs is to replace inefficient lighting technologies in residential and commercial environments, which traditionally have primary access to the ac power grid, in accordance to their aforementioned advantages. In that sense, Fig. 2 shows the expectations for the lighting market until 2022. As can be seen, LEDs are supposed to replace incandescent light and even start to replace compact fluorescent lights by that date.

Considering the inherent behaviour of the LEDs as a diode, only allowing the current to go across it in one direction, it is necessary to use an ac–dc converter to ensure that the LEDs are driven with an adequate dc current. The reason behind

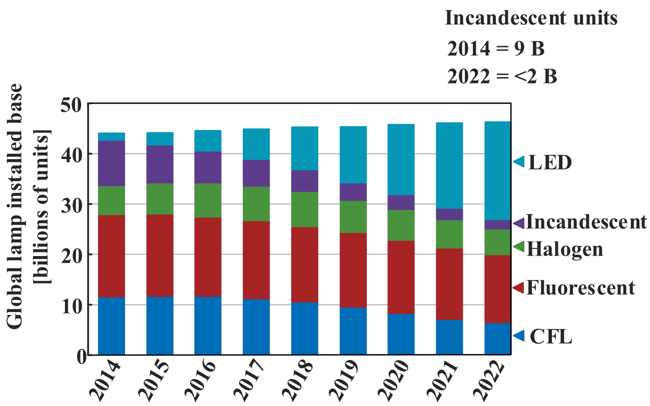


Fig. 2. Expectations of global installed base of lamps in terms of light-source technology [12].

requiring this power conversion comes from the fast current–light response from the LEDs, which could replicate the sinusoidal current from the grid at double the mains frequency causing an undesirable visible flicker to occur. In fact, this requirement has made the driving of LEDs from the mains an important research topic in a wide range of power [13]. In accordance to previous literature, an ac–dc LED driver needs to be: efficient, compact, operate in universal voltage range, comply with specific regulations for LED drivers (discussed in Section II), have a lifetime comparable to that of LEDs, and control the current across the LED load in order to perform dimming and achieve an adequate light output. Taking into consideration the aforementioned characteristics, Fig. 3 shows at a glance, the proposed classification for ac–dc LED drivers for both single-phase and three-phase ac power grids in terms of the number of power conversion stages used. A distinction between single-phase ac–dc LED drivers and three-phase ac–dc LED drivers is made taking into account that three-phase ac–dc LED drivers are proposed for high-power LED loads (i.e., > 300 W). In addition, single-phase solutions are divided between active and passive, considering the latter are more prone to be used for LED lamps (i.e., < 25 W), whereas active solutions are used for both LED lamps and LED luminaires (i.e., > 25 W). The different solutions will be further detailed along Section III for single-phase ac–dc LED drivers and Section IV for three-phase ac–dc LED drivers, considering the latest trends with a special focus on the aforementioned requirements that an ac–dc LED driver should comply with.

The last section will be dedicated to the conclusions that can be extracted from the comprehensive study carried out on the latest trends for ac–dc LED drivers after reviewing and classifying over 200 publications.

II. Regulations and Recommendations for AC–DC LED Drivers

The regulations that an LED driver needs to comply with are to be understood before discussing which solutions are the most appropriate. This section focuses on specific regulations and recommendations for LED drivers, such as: the ENERGY STAR program requirements product specification for luminaries, harmonic standard (i.e., IEC 61000-3-2), and flicker regulations and metrics.

A. *ENERGY STAR*

ENERGY STAR summarizes a series of requirements for LED lighting products to achieve their seal of approval, including the LED load and the ac–dc LED driver. In addition, the regulation differentiates between two kinds of LED loads: LED lamps and LED lighting fixtures (i.e., LED luminaires), and excludes a series of products, such as, solid state retrofits, high bay fixtures, outdoor street, and area lighting and party or entertainment lighting [14]. Nonetheless, it still covers a wide spectrum of LED lighting products both in residential and commercial environments.

Of the aforementioned requirements, the first one is directed to lamps intended to replace incandescent light bulbs [15], whereas the second is intended for most lighting products intended for direct connection to the power grid with an input power below 250 W [16]. Specifically, Table I lists the requirements that the ac–dc LED driver needs to meet in order to comply with ENERGY STAR. From this list, it should be noted that the most restrictive constraints are the rated life and the power factor (PF). The first, because it requires the ac–dc LED driver to last longer than 10 000 h, which is the rated lifetime of the most restrictive component frequently used in ac–dc LED drivers, the electrolytic capacitor [17]. The second, since its compliance drastically reduces the possible topologies that can be used for its design, as an almost sinusoidal current waveform in phase with the voltage needs to be guaranteed at the input of the LED driver. It should be noted that those ac–dc LED drivers that have an input power of less than 5 W and a PF of more than 0.5 would fall into the low PF subcategory previously introduced in Fig. 3.

B. *Harmonic Injection Standard, IEC 61000-3-2*

Over the last few decades, the rise of non-linear loads connected to the grid has caused the amount of low frequency (LF) harmonics to increase. The increase is principally caused by the usage of inadequate ac–dc converters that demand non-sinusoidal currents with a low PF. In fact, a diode bridge followed by an electrolytic capacitor is commonly used in low cost applications causing the current to be demanded as short duration current peaks.

In order not to cause the quality of the grid to decrease, the International Electrotechnical Commision (IEC) released several regulations to limit the LF harmonic injection from electronic equipment to the grid. For the scope of this paper, the IEC 61000-3-2 regulation, which limits the harmonic injection in equipment that draws input currents of ≤ 16 A per phase, is going to be considered as an indispensable requirement in the design of ac–dc LED drivers. The regulation details how the LF harmonics of the input current (i.e., the first 40 from the fundamental frequency) need to be limited and measured depending on the classification summarized in [18]. According to this classification, lighting equipment falls under the Class C category for single-phase ac power grids. However, the

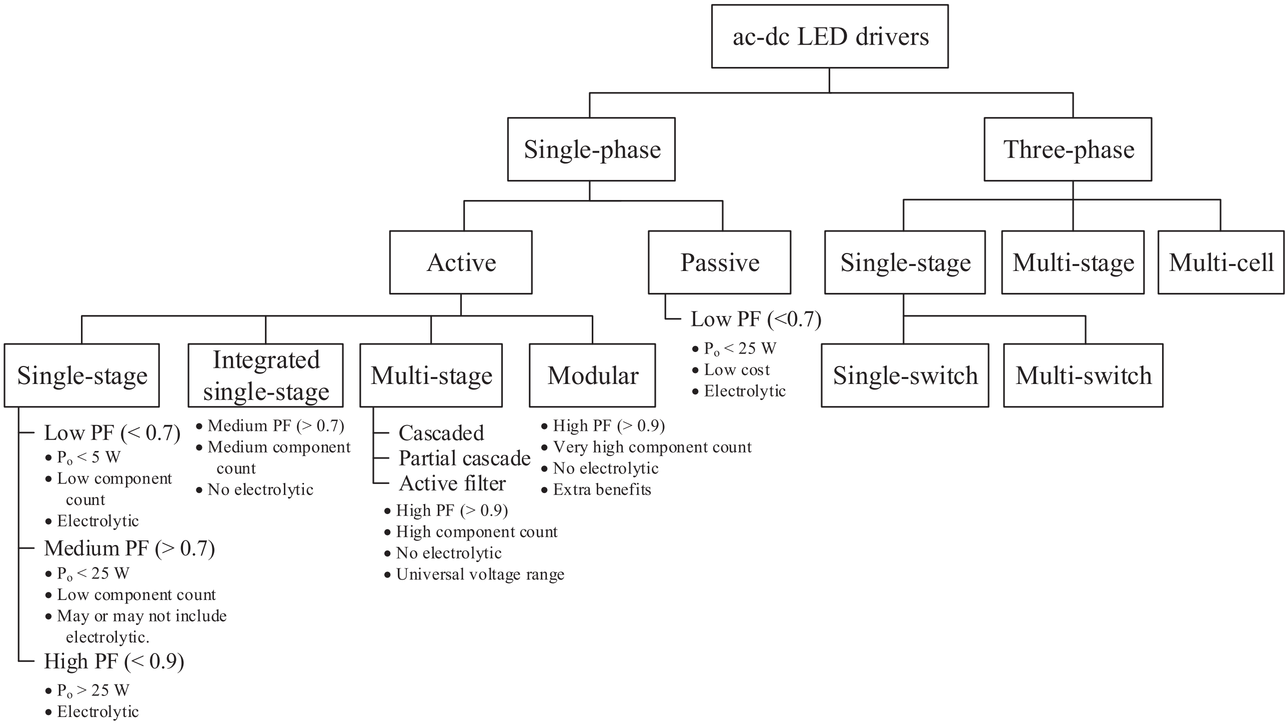


Fig. 3. Classification of ac–dc LED drivers for both single-phase and three-phase ac power grids.

TABLE I
LED DRIVER REQUIREMENTS, IN ACCORDANCE TO ENERGY STAR [16]

Rated Lifetime	The LED package(s) / LED module(s) / LED array(s), including those incorporated into LED light engines or retrofit kits, shall meet the following L_{70} lumen maintenance life values: • $L_{70} \geq$ 25,000 hours for indoor. • $L_{70} \geq$ 35,000 hours for outdoor. • $L_{70} \geq$ 50,000 hours for inseparable luminaires. Note: L_{70} defines the elapsed operating time over which the LED light source will maintain a 70% of its initial light output.
Source Start Time	Light source shall remain continuously illuminated within 1 second of application of electrical power.
Power Factor	Total luminaire input power ≤ 5 watts: PF ≥ 0.5. Total luminaire input power > 5 watts: PF ≥ 0.7.
Standby Power Consumption	Luminaires shall not draw power in the off state.
Operating Frequency	Lamp light output shall have a frequency ≥ 120Hz.
Transient Protection	Ballast or driver shall comply with ANSI/IEEE C62.41.1-2002 and ANSI/IEEE C62.41.2-2002, Category A operation. The line transient shall consist of seven strikes of a 100 kHz ring wave, 2.5 kV level, for both common mode and differential mode.
Dimming Performance	The luminaire and its components shall provide continuous dimming from 100% to 20% of light output. Note: This only applies for certified dimmable luminaires.
Audible noise	Luminaire shall not emit noise above 24 dBA at 1 meter or less at the minimum output.

regulation is not clear at stating under which category falls a balanced three-phase equipment for lighting applications as it falls in both Class A and Class C. Consequently, this specific equipment will be considered as Class C due to its more restrictive nature over Class A.

Furthermore, Class C differentiates two scenarios depending on the active input power of the lighting equipment. If the power exceeds 25 W (i.e., luminaires), then the harmonic content of the input current needs to be limited in terms of a certain percentage of the fundamental harmonic (i.e., Class C limits of the work presented in [18]), taking into account that the third harmonic is also limited by the PF of the input current. However, if that is not the case and the active input power is below or equal to 25 W (i.e., LED lamps), then the input current needs to either have its harmonic components limited by a set of maximum values per harmonic (i.e., Class D limits of the work presented in [18]), or fulfill a set of conditions. These conditions shape the waveform requiring that the third and the fifth harmonic component of the current shall not exceed 86% and 61% of the fundamental current, respectively. In the latter, these conditions need to be achieved while fulfilling that the input current reaches 5% of its crest value at 60° or before, that its crest is reached at 65° or before. In addition, its value is required not to fall below 5% of its crest value before reaching 90°, referred to any zero cross of the input voltage, as can be seen in Fig. 4. The ac–dc LED drivers that comply with this condition will be considered as medium PF.

It can be concluded, taking into account the preceding requisites, that the regulation is laxer for lighting equipment below 25 W. In that sense, this broadens the study of topologies that can distort the input current to a certain extent while still achieving a low cost solution. However, this is not the case for equipment exceeding 25 W, as Class C limits are considered the most restrictive of the four classes detailed in IEC 61000-3-2. This

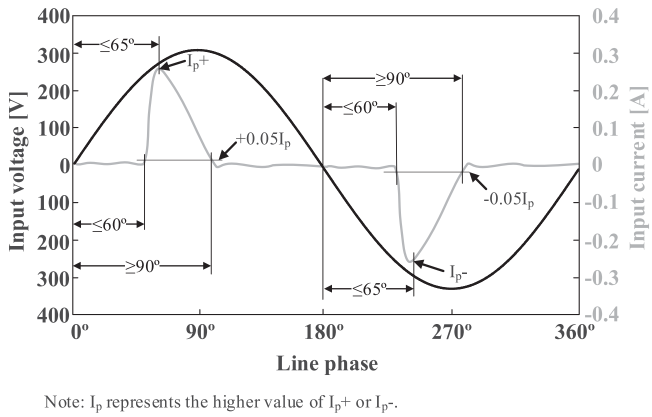


Fig. 4. Illustration of the relative phase angle and current parameters [18].

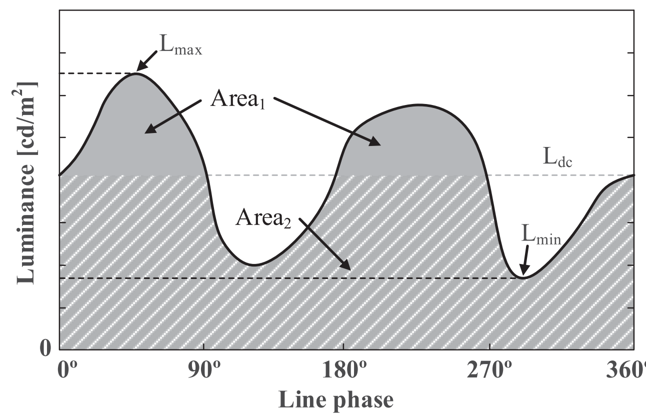


Fig. 5. Illustration of the luminance over the line phase to exemplify the estimation of flicker index and Mod. (%).

implies that the current shape needs to be sinusoidal and aligned with that of the input voltage, which normally means achieving unity PF, thus those ac–dc LED drivers that need to comply with this regulation will be classified into the high PF subcategory. This characteristic limits ac–dc LED drivers of more than 25 W to those topologies that can achieve power factor correction (PFC), as will be seen in Section III, and understanding PFC as the ability of demanding a sinusoidal current in phase with the input voltage, thus achieving unity PF.

C. Flicker Metrics

The flicker phenomenon can be defined in terms of any lighting equipment as a rapid repetitive change in luminance [19]. Particularly, in the case of LEDs, it occurs due to the fast response to current variations. Precisely, the harmonic content of the current flowing across the LEDs translates into a light output modulated by those components. However, not all frequency components are equally harmful for humans, and only those below 3 kHz can be considered as such. In fact, whether the LF modulation is visible or invisible, it can trigger headaches, migraines, fatigue, epilepsy, or any other neurological response [20].

Reducing flicker harmful effects has become increasingly important for ac–dc LED drivers, since conceptually double the mains frequency can easily appear at the current across the LEDs. For instance, without a proper flicker regulation, the output capacitor of the ac–dc LED driver that decouples the ac component of the current across the LEDs and thus controls the admissible ripple of the current, can be overestimated causing the life expectancy of the ac–dc LED driver to decrease or underestimated causing flicker to appear. Therefore, the flicker recommendation truly sets the limits on the allowed amplitude of the luminance and as such, the size of the output capacitance. For that matter, two simple metrics were defined in order to give a measure of flicker [20]:

1) Flicker index [21] is defined as the area above the line of average luminance (i.e., L_{dc}) divided by the total area of the light output curve during a cycle, see Fig. 5

$$\text{Flicker index} = \frac{\text{Area}_1}{\text{Area}_1 + \text{Area}_2}. \tag{1}$$

This metric has been developed for fluorescent lamps and has the advantage of taking into account the waveform shape.

2) Percent flicker [21], also known as Modulation (%), which is the preferred expression due to its relationship with the ripple of the luminance waveform, can be defined as

$$\text{Mod. } (\%) = \frac{\mathrm{L_{max}} - \mathrm{L_{min}}}{\mathrm{L_{max}} + \mathrm{L_{min}}} .100 \tag{2}$$

where $L_{\max}$ and $L_{\min}$ define the maximum and minimum luminance that the LEDs are producing, respectively.

The issue with the aforementioned definitions is their independence from the frequency of the signal and the lack of a relationship with human perception. In the last decade, efforts toward a set of recommendations have been made due to the lack of association between flicker and frequency in previous literature. Actually, the requirements in terms of flicker should not be the same for frequencies below 90 Hz than for those that are higher, since human eyes are more sensitive to those lower frequencies [22].

Nowadays, there is still no such thing as a flicker regulation, but a several sets of complex flicker metrics. On that note, one of the first proposal was done by the IEC 61000-4-15:2012 [24]. This regulation defines a set of specifications that a flickermeter needs to meet. The main problem with this definition is that the allowed fluctuations are not limited in an adequate frequency range, particularly going from 0.5 to 40 Hz. The latter is of utter importance considering how sensitive humans are to frequencies up to 90 Hz.

In 2015, the IEEE standard 1789-2015 defined a recommendation of practices [23]. These practices are summarized in Table II and take into account the frequency of the luminance up to 3 kHz. It should be noted that out of the three practices detailed, Practice 2 is the most restrictive one, ensuring no observable effect level (NOEL). Nonetheless, the designer needs to typically aim to comply with Practice 1, as it is restrictive enough to limit hazardous biological effects.

Furthermore, the light output of any lighting equipment connected to an ac power grid can contain several harmonics related

TABLE II
RECOMMENDED PRACTICES, IN ACCORDANCE TO IEEE STD. 1789-2015 [23]

Practice 1	If it is desired to limit the possible adverse biological effects of flicker, then flicker Mod. (%) should satisfy the following goals: • Below 90 Hz, Mod. (%) is less than 0.025×frequency. • Between 90 Hz and 1250 Hz, Mod. (%) is below 0.08×frequency. • Above 1250 Hz, there is no restriction on Mod. (%).
Practice 2	If it is desired to operate within the recommended NOEL of flicker, then flicker Mod. (%) should be reduced by 2.5 times below the limited biological effect level given in Recommended Practice 1: • Below 90 Hz, Mod. (%) is less than 0.01×frequency. • Between 90 Hz and 3000 Hz, Mod. (%) is below 0.0333×frequency. • Above 3000 Hz, there is no restriction on Mod. (%).
Practice 3	For any lighting source, under all operating scenarios, flicker Mod. (%) shall satisfy the following goal: • Below 90 Hz, Mod. (%) is less than 5%.

to the fundamental frequency of the grid (i.e., 50 Hz for Europe and 60 Hz for the US), or even subharmonics below those frequencies due to failures either in the driver or the grid, which can be potentially hazardous. In those cases, the recommendation is clear, stating that all the harmonic components of the measured luminance over a line cycle should lie within the limits stated in the selected practice from Table II.

Two important issues appear with this practice. The first one is that some lighting fixtures, as incandescent light bulbs are deemed not safe in accordance to this practice. The second is the discontinuity that appears close to 90 Hz, which is inconsistent considering this to be a reflection of a biological response. In addition, the IEEE 1789-2015 standard can only be applied to sinusoidal waveforms [25]. Nonetheless, the following recommendations truly ensure a flicker-free performance.

Another flicker metric of importance has been proposed by the Alliance for Solid-State Illumination Systems and Technologies (ASSIST) [26]. This metric is based on measuring the light output of a certain light source and performing a series of mathematical operations to yield a metric value that needs to be necessarily below one to ensure a flicker free performance. The first step is acquiring a sampled waveform of the luminance at a recommended sampling rate of 2000 samples/s during 2 s. Then, the Fourier transform is applied to this waveform in order to obtain the amplitude of each of the components that comprise the luminance waveform. These components are used to attain Mod. (%) at each frequency, which are, then, weighed accordingly with a human eye sensitivity curve. Finally, the weighed components are summed with a quadrature sum to attain the desired metric value [26].

Even though this method is extended to any kind of waveform and not only to sinusoidal waveforms as the IEEE 1789-2015, its weakness lies in not considering the flicker sensitivity in the range between 100 and 200 Hz [25].

In 2017, the National Electrical Manufacturers Association (NEMA) proposed a criterion to determine the safety of a temporal light artifact [27]. The methodology for low frequencies (i.e., < 80 Hz) is based on the IEC 61000-4-5:2012 (defining the P_{st} parameter within) and is completed for high frequencies (i.e., > 80 Hz) with the Stroboscopic Visibility Measure (SVM). In fact the SVM is based on the methodology proposed by [28]. The NEMA 77:2017 requires P_{st} to be lower than one for both outdoor and indoor applications and only limits SVM for indoor applications at 1.6. This criterion is not as restrictive as the IEEE 1789:2015 but addresses the main problem it had with incandescent lights. The main drawback is that it can only be applied to sinusoidal waveforms.

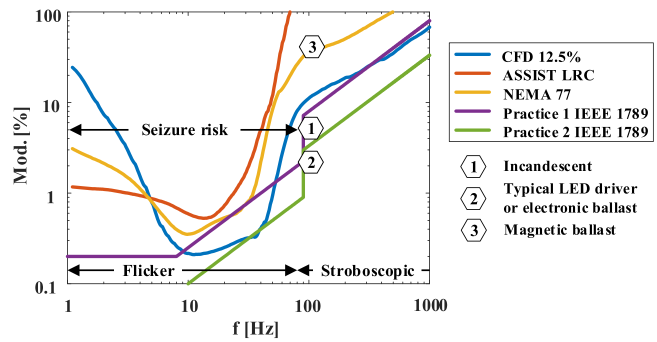


Fig. 6. Comparison of different flicker metrics in terms of the allowed Mod. (%).

The last flicker meter that is going to be discussed is the compact flicker degree (CFD), which essentially works as ASSIST LRC, but in this case taking into account all Fourier frequencies up to 2 kHz, thanks to its different human eye sensitivity function, instead of stopping at 100 Hz. Then, a metric is generated by summing all the weighted Mod. (%). In order to achieve a flicker free performance, the CFD metric needs to be less than 1%, considering imperceptible those values between 1% and 12.5%, and acceptable and rarely perceived by humans the range between 12.5% and 25% [25]. In addition, this parameter can be used with any light waveform.

Fig. 6 shows a comparison between all the aforementioned flicker metrics in terms of the allowed Mod. (%) at each frequency. As can be seen Practice 2 of the IEEE 1789-2015 is the most restrictive of all the discussed flicker metrics, considering that even incandescent lamps are considered to have flicker, whereas NEMA 77 can be considered less restrictive. It should be noted that the IEC 61000-4-5:2012 curve is represented within the NEMA 77 curve from 1 to 80 Hz, as this flicker metric is based on it under that frequency range. However, from that point onward the IEC 61000-4-5:2012 curve follows the ASSIST LRC curve that does not consider the higher frequencies to cause any harmful effect.

In order to address the presented flaws within each criterion, the International Commission of Illumination is currently working in a standard that is able to clearly state and define a flicker regulation [29]. Nonetheless, and considering all these different metrics, the one thing that they do have in common is that they set very specific rules to the admissible fluctuations of the light at certain frequencies, which in the case of LEDs is translated to the admissible ripple of the current. Particularly, for ac–dc LED drivers this ripple is completely reliant on the value of the output capacitance that buffers the pulsating power from the ac mains, meaning that as long as this capacitor is big enough, a flicker-free performance can be guaranteed. The problem present is that in most cases an electrolytic capacitor will be required in order to meet the required current ripple across the LED load. For that matter, the flicker-free condition will determine whether an electrolytic capacitor-less ac–dc LED driver can be achieved for the different solutions that will be discussed in this paper.

It is important to note that depending on the flicker metric or the LEDs used the size of the capacitor will differ, meaning that while some flicker metrics will be able to dispose of the electrolytic capacitor for certain LED strings others will not. For this reason whenever a topology is considered to remove the electrolytic capacitor, this will be evaluating the strictest regulation set by Practice 1 of the IEEE 1789-2015.

III. Single-Phase AC–DC LED Drivers

Considering that the primary access in homes, streets, and offices is single-phase ac, the use of an ac–dc converter it is required in order to drive an LED load (i.e., ac–dc LED driver), to guarantee a flicker free performance. However, several distinctions can be made depending on the LED load to drive. In fact, the regulations (i.e., ENERGY STAR and IEC 61000-3-2) differentiate between two rules in function of the input power of the LED load. The laxer regulation set for LED lamps (i.e., lighting products of less than 25 W) makes possible the usage of simple, and inexpensive passive solutions, whereas LED luminaires (i.e., lighting products of more than 25 W) need to comply with the most restrictive set of rules, requiring the use of a PFC solution.

A. Passive

Passive solutions, normally applied to retrofit/replacement lamps of less than 25 W, require the least components of all the solutions that are going to be discussed along this section. In this case, the input current of the driver is not required to be sinusoidal in accordance to Class D regulation or to the graphic limits set by Fig. 4, allowing some degree of distortion to happen in the input current. In contrast, some benefits are traded off:

1) the ability to control the current, unless a trimmer that will further distort the current is used [30]. The addition of a trimmer may also cause flicker to appear under dimming conditions;
2) the lower lifespan of the lamp, due to the inability to remove the electrolytic capacitor;
3) the efficiency, due to the resistive elements introduced to limit the peak current.

The conventional passive solution, depicted in Fig. 7(a) and (b), is based on using a capacitor-input filter to generate a dc voltage in order to feed the LED load at either high voltage [31] or low voltage [32]. It should be noted that the current across the low voltage solution is phase shifted 90° with respect to the input voltage allowing the conducting angle to increase. The current across the LED load for both passive solutions is not controllable and resistor R_B needs to be included to limit the peak current. The inclusion of this resistive element hinders the efficiency of the solution. Another possibility to drive LEDs passively is depicted in Fig. 7(c); this solution is based on using the LED load to rectify the input voltage, thus using a string for the positive half-line cycle and the other one for the negative half-line cycle. This technique is referred in literature as LF AC-LED driving [33]–[38], and presents two important drawbacks: the first is the LF flicker due to the driving of the LEDs with a sinusoidal current, and the second is that the amount of LEDs used is duplicated when compared to the capacitor-input filter solution. In contrast, the efficiency is increased and the lifetime of the driver is prolonged, as the electrolytic capacitor is not required considering the ac driving does not have an impact on the lifespan of the LEDs in accordance to the work presented in [39]. It should be noted that there have been some proposals to reduce the amount of LEDs used in this solution; however, the number is always greater than the conventional solution [36]. Furthermore, the limiting resistance is still required. Other solutions have replaced the limiting resistance by a capacitor to passively balance several LED strings [40], method that was widely used in cold cathode fluorescent lamps, or even inductors in series with the string [41]. The latter, would increase the size of the ac–dc LED driver significantly due to the LF inductors required, and its use is mainly recommended for high frequency (HF) AC-LED driving.

In order to solve some of the aforementioned problems, some authors have proposed using a valley-fill circuit in conjunction with an output inductance [42]–[44]. This configuration reduces the harmonic content of the input current and eliminates the electrolytic capacitor, thus improving the lifespan of the ac–dc LED driver, see Fig. 8(a). In contrast, other authors have included complex input filters to improve the total harmonic

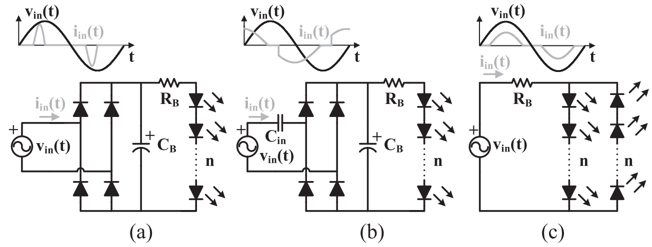


Fig. 7. Typical passive solutions to drive LEDs from ac single-phase power grids. (a) Capacitor-input filter [31]. (b) Voltage-step-down capacitor-input filter [32]. (c) Conventional AC-LED driver [36].

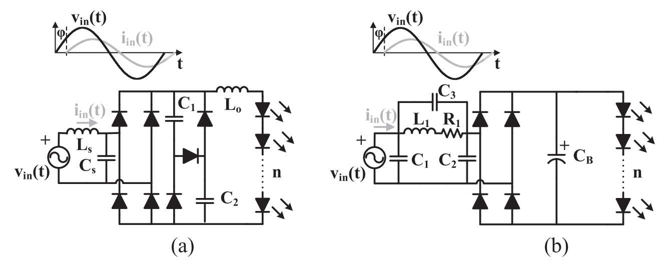


Fig. 8. State-of-the-art passive solutions to drive LEDs from ac single-phase power grids. (a) Valley-fill circuit-based [42]–[44]. (b) Filter-based [45].

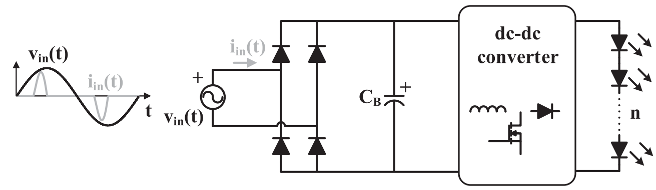
distortion (THD) and PF, improving the scope of the passive solutions to not only drive low-power luminaires, but to not eliminating the bulk capacitor, see Fig. 8(b) [45]. However, the tradeoff that comes with these kind of solutions is the increased cost due to the amount of components and the inclusion of LF bulky inductors that will increase the size and weight.

B. Active

Active single-phase ac–dc solutions are defined by one or various active components that are controlled in order to shape the input current while keeping a dc output voltage/current. The analysis carried out is focused on switch mode power supplies considering that linear regulators are extremely inefficient for this purpose [65].

One way to classify active ac–dc LED drivers, following Fig. 3, depends on the amount of power stages included in the ac–dc LED driver. In that sense, an ac–dc LED driver comprised by a single power stage would fall into the single-stage category, whereas a driver with two or more cascaded power stages will fall into the multi-stage category. Those ac–dc LED drivers that fall in between, based on the integration of two stages would be classified into integrated single stages. Moreover, the addition of a power stage that does not process all the power will be classified as a multi-stage solution, even if they are normally referred as quasi- or pseudo-single-stages [64], [85], [88], [89], [91]–[105], [119], [121]–[133], [140]–[155]. In this classification, an extra category is added in order to include those drivers comprised of more than one power stage connected in any of the modular configurations: input series output parallel, input parallel output series, input series output series, or input parallel output parallel. Furthermore, within the previous categories, some design conditions should be distinguished. First, the inclusion of galvanic isolation or not, which is a recommended practice to isolate the normally safe voltages withstood by the LED load from the grid; second, the input power of the luminaire and its implication over the allowed PF or input current shape depending on the regulation; and last, the removal of the electrolytic capacitor. Accordingly, different solutions can be yielded when conceiving these distinctions.

1) Single-Stage Solutions: Active single-stage ac–dc solutions are massively used in ac–dc LED drivers due to their low cost and simplicity over the conventional two-stage solution. In contrast, some limitations appear on the requirements set at the start of this section: the electrolytic capacitor cannot always be removed, the efficiency tends to be low (i.e., $< 90\%$), a universal input solution can be difficult to be achieved, and the dc voltage conversion ratio can be required to be rather high. In fact, one of the biggest issues is that a tradeoff between the benefits needs to be made, as an example; a single-stage ac–dc LED driver may be unable to provide both dimming and universal input voltage range. Therefore, taking into account the previous facts, single-stage solutions can be further classified in terms of their input power into two different categories: LED lamps and LED luminaires in accordance to IEC 61000-3-2 input power distinction. The less than 25 W category engulfs both low PF and medium PF categories introduced in Fig. 3. As a reminder, the low PF subcategory is defined in accordance to ENERGY STAR for those ac–dc LED drivers of less than 5 W of input power that also require a PF of more than 0.5. The medium PF subcategory is defined for those LED drivers of less than 25 W of input power that need to comply with the Class D of the IEC 61000-3-2. The high PF subcategory is last defined for those ac–dc LED drivers of more than 25 W that need to meet the requirements of Class C of the IEC 61000-3-2 regulation, which is an almost sinusoidal input current in phase with its input voltage.



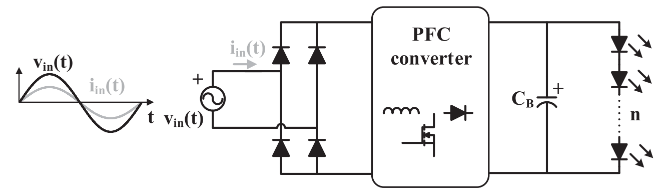


Fig. 9. (a) Single stage based on a capacitive input filter for low and medium PF. (b) Single stage based on a single-stage LFR for high PF.

The simplest approach to design a single-stage ac–dc LED driver for LED lamps can be found in Fig. 9(a), based on having a capacitive input filter followed by a dc–dc converter. The capacitive input filter yields a constant voltage at the input of the dc–dc converter. The dc–dc converter then controls the current fed to the LED string. The issues with this approach are its low PF and the inability to remove the electrolytic capacitor. However, some authors have been able to remove the electrolytic capacitor while achieving a flicker-free performance and complying with IEC 61000-3-2 in terms of the input current waveform, see Fig. 4, by means of an asymmetrical half-bridge flyback converter [46].

The other approach to design a single-stage ac–dc LED driver for both input power ranges is depicted in Fig. 9(b) using a dc–dc converter operating as a loss free resistor (LFR). This approach is able to attain a sinusoidal input current waveform in phase with its input voltage with a correct selection of the PFC converter and its control. The main drawback is the inability to remove the electrolytic capacitor while guaranteeing a flicker free performance due to the power pulsation of the mains.

The removal of the electrolytic capacitor is normally performed with a second stage that compensates the LF ripple on the output voltage in order to attain an ac–dc LED driver with a lifetime comparable to that of the LEDs. However, achieving this performance in a single-stage ac–dc converter is not an easy task, and more components are required. In that sense, some authors propose the use of valley-fill circuits [47]–[49] as what was shown in Fig. 8(a) for passive solutions. The

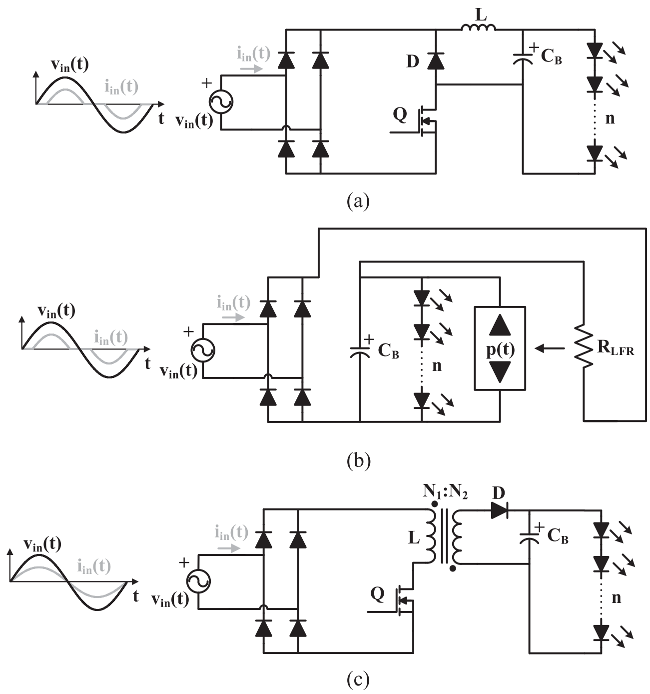


Fig. 10. Some examples of LED drivers for retrofit lamps. (a) Buck converter [54]–[59], [129]. (b) Equivalent circuit of the LFR-based AICS [84]. (c) PFC flyback converter [70]–[86].

proposal is able to remove the electrolytic capacitor at the cost of having an increased amount of passive components and a low efficiency.

Another alternative to remove the electrolytic capacitor, in single-stage ac–dc converters, is distorting the input current. Some authors have proposed the injection of the third, fifth, or even seventh harmonics attempting to reduce the heavy pulsation of the input power if a pure sinusoidal current is demanded [50]–[53]. The analysis shows for ac–dc LED drivers that requirements with ENERGY STAR can be met in terms of PF. However, ensuring compliance with Class C IEC 61000-3-2 still requires the use of an electrolytic capacitor. Hence, the distortion of the input current is particularly interesting for ac–dc LED drivers dedicated to retrofit LED lamps (i.e., < 25 W). This opens a handful of simple active solutions, even if the electrolytic capacitor is not removed considering the cost is the main concern for this application, as are: the use of active input current shapers (AICS), or buck converter and its multiple variants, normally neglected for PFC.

Several solutions for retrofit LED lamps have been proposed based on using non-isolated buck converters either as a single stage or quasi-single-stage [54]–[59], [129], see Fig. 10(a), isolated converters from the buck family [46], [60], using an LFR as the limiting resistor rendering an AICS [84], as depicted in Fig. 10(b). The converters from the buck family show better efficiencies than the ones from the buck-boost family, with the limitation of the conducting angle that is only able to comply with the regulation set for LED lamps.

Before continuing on discussing the different topologies used in ac–dc LED drivers, it is important to define the LFR concept. An LFR is a dc–dc converter behaving as a resistor at its input and as a power source at its output by means of control [61], [62]. The resistive value of the LFR (i.e., R_{LFR}) depends on a certain control variable, v_c. This is a well-known concept in the ac–dc PFC field, where a sinusoidal current in phase with the input voltage of the converter is desired [63].

As regards the solution based on using an LFR [i.e., Fig. 10(b)] to limit the current on the LEDs, it should be noted that it is able to achieve a high step-down ratio between input and output voltage with a simple approach requiring an isolated converter working as an LFR. This solution slightly distorts the input current demanded rendering an AICS, whose main drawback is its inability to remove the electrolytic capacitor [84].

That being said, the simplest and most massively used converter in single-stage ac–dc LED drivers for both power ranges, with its multiple variants, is the flyback converter in accordance to previous reviews on the topic [65]–[68]. A flyback converter, see Fig. 10(c), is a converter from the buck-boost family that includes galvanic isolation thanks to its coupled inductor [69]. By being a member of the buck-boost family, it is able to achieve unity PF and PFC naturally by working in discontinuous conduction mode (DCM), which simplifies its control. In contrast, the converter is unable to remove the electrolytic capacitor while ensuring a flicker-free performance, and it suffers from low efficiencies because of being a converter from the buck-boost family that requires a passive snubber, used in low cost solutions, to protect the main switch from voltage spikes caused by the leakage inductance of the couple inductor [70]–[86].

Delving into single-stage ac–dc LED drivers for luminaires (i.e., > 25 W) most of the topologies are shared topologies with the retrofit ones, as long as they demand a sinusoidal current [72]. In the case of luminaires, the preferred solutions are focused around the buck-boost and the boost converter family. The first is able to provide the LED with lower voltages while keeping a sinusoidal current. Among the non-isolated buck-boost family solutions: the buck-boost [92]–[102], the Ćuk [107]–[110], the SEPIC [100]–[105], [111]–[113], and the Zeta [114] converters can be found. The last three are normally avoided in low cost applications due to their increased number of components [115], [116]. In fact, their isolated variants are barely used in ac–dc LED drivers due to the versatility of the flyback converter and the fact that their integrated stages with an isolated or non-isolated dc–dc converter tend to be more efficient, able to remove the electrolytic capacitor, and have a lower component count [67].

The boost converter can also be used in single-stage ac–dc LED drivers for luminaires. However, the necessity to work with higher voltages has made the use of this converter situational due to the amount of LEDs required in series for the LED load, which is not a recommended practice in terms of reliability. Nevertheless, the advances in LED technology have made possible the use of an ac–dc single-stage boost converter to drive high voltage LEDs [117], [118]. Otherwise, a boost integrated with a step-down dc–dc converter can be used to drive LEDs, being either a conventional [87]–[93], [177] or a bridgeless PFC boost [94]–[97]. The latter has the same operation as a conventional boost, but the LF diode bridge is removed in order to achieve an improvement in its efficiency.

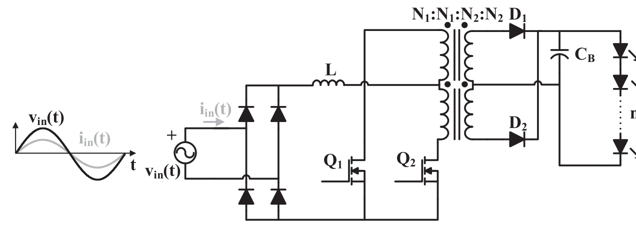


Fig. 11. Example of isolated boost based ac–dc LED drivers for luminaires based on a current-fed push–pull [135].

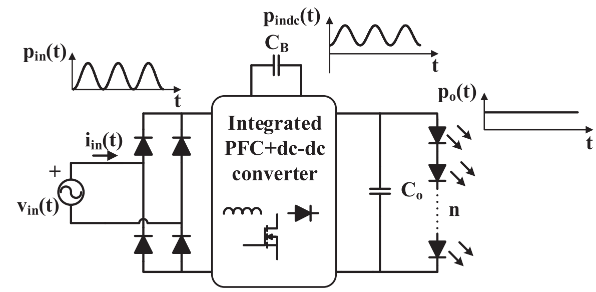


Fig. 12. Integration of a two stage into a single stage with common active components [87]–[133].

The isolated variations of the boost converter family, also referred as current-fed isolated converters, are rarely used in PFC due to the several issues they present, such as, complex transformer design, the need for demagnetization path for their main inductance or inductances, or complementary signals in comparison to the traditional controllers. Furthermore, due to the lack of commercially available analog controllers for the driving of current-fed topologies, the control is normally implemented digitally, which for this particular application can be considered a drawback as its cost and complexity increases.

It is because of these issues that their potentially higher efficiency is hindered achieving a similar level to that of the buck-boost family isolated converters [134]. Nonetheless, some works of single-stage ac–dc current-fed isolated converters have been proposed in literature, such as, a current-fed push–pull [135], see Fig. 11, a dual inductor current-fed push–pull [136], or a current-fed full-bridge [137]. In the previous literature, the use of these topologies to implement ac–dc LED drivers can be found, particularly a push–pull converter in [138] and a dual inductor current-fed push–pull in [136]. The first proposal does not address any of the aforementioned issues, achieving a very low efficiency while suffering at the same time from high voltage stress on the main switches. In contrast, the dual inductor current-fed push–pull reduces the stress on the main switches, achieves a high efficiency (i.e., $> 90\%$) and reduces the input current ripple thanks to the interleaving that occurs between is two input inductances. However, it is unable to remove the electrolytic capacitor if a flicker-free solution wants to be achieved.

As regards the dynamic response of single-stage ac–dc LED drivers, it is normally slow due to the low bandwidth output current loop required to filter the LF harmonics from the mains that appear on the output current. This is not the case for most solutions that integrate a two-stage ac–dc LED driver or in the upcoming multi-stage ac–dc LED drivers, as the second stage can provide a higher bandwidth. Nonetheless, the dynamic response is unimportant for LEDs as they are considered a slow load for illumination products, as long as the LF output ripple is cancelled [8]. In addition, the control of the proposed solution follows a traditional approach that can be typically implemented with a commercial analog IC, which simplifies its control and reduces the cost of the LED driver.

2) Integrated Single-Stage Solutions: One of the most used methods to achieve a single stage that is able to remove the electrolytic capacitor without incurring into flicker falls into what can be considered a quasi-single-stage. This method combines typically well-known topologies of the first and the second stages under shared switches [87]–[105], [119]–[133] based on the concept proposed in [106], see Fig. 12.

The integrated single-stage bases its operation on allowing a certain ripple on C_B. However, this ripple is cancelled at the output of the converter with the help of a control loop included in the dc–dc converter stage that is able to correct the LF variations. In particular, this case follows the same principle used in two-stage solutions that will be discussed later in Section III-B3. Then, it is not unexpected that the presented topologies are based on the most popular multi-stage solutions. However, the rendered topologies are not as efficient as the two-stage solutions that they come from, due to stress happening on the switches as a consequence of sharing operation for both stages, and in most cases they still perform a double power conversion. In the end, it is a matter of making a tradeoff for a more cost effective solution with a higher power density, and without a flicker and an electrolytic capacitor.

It should be noted that within this category falls the traditional AICS approach, its operation is based on integrating an AICS with a dc–dc converter. This solution is able to remove the electrolytic capacitor allowing a certain ripple to appear on the intermediate bus capacitor (i.e., C_B), causing some distortion to appear on the input current. The drawbacks of this solution are its low efficiency, and its narrow input voltage range operation due to the difficulties to limit the voltage on C_B while keeping a PF below 0.7 and an efficiency higher than 80% [64], [85]. Hence, its use for medium PF ac–dc LED drivers.

3) Multi-Stage Solutions: Conventionally, in PFC, two-stage solutions have been used to drive dc loads, see Fig. 13(a) [63]. The first stage is dedicated exclusively to perform PFC by using topologies that could achieve unity PF and provide the second stage with an almost constant voltage with a certain ripple. Consequently, the second stage is dedicated to ensure an adequate voltage or current level on the LED load. In addition, it is required to correct the LF ripple that appears due to the lower capacitive value of C_B to achieve the removal of the electrolytic capacitor, which causes the power to slightly pulsate at the input of the dc–dc converter [p_{indc}(t)]. It should be noted that for the power range in which the multi-stage solution is used (i.e., the driving of LED luminaires), the inclusion of galvanic isolation is recommended and tends to be mandatory. In fact, galvanic isolation can be included in either the first or the second stage.

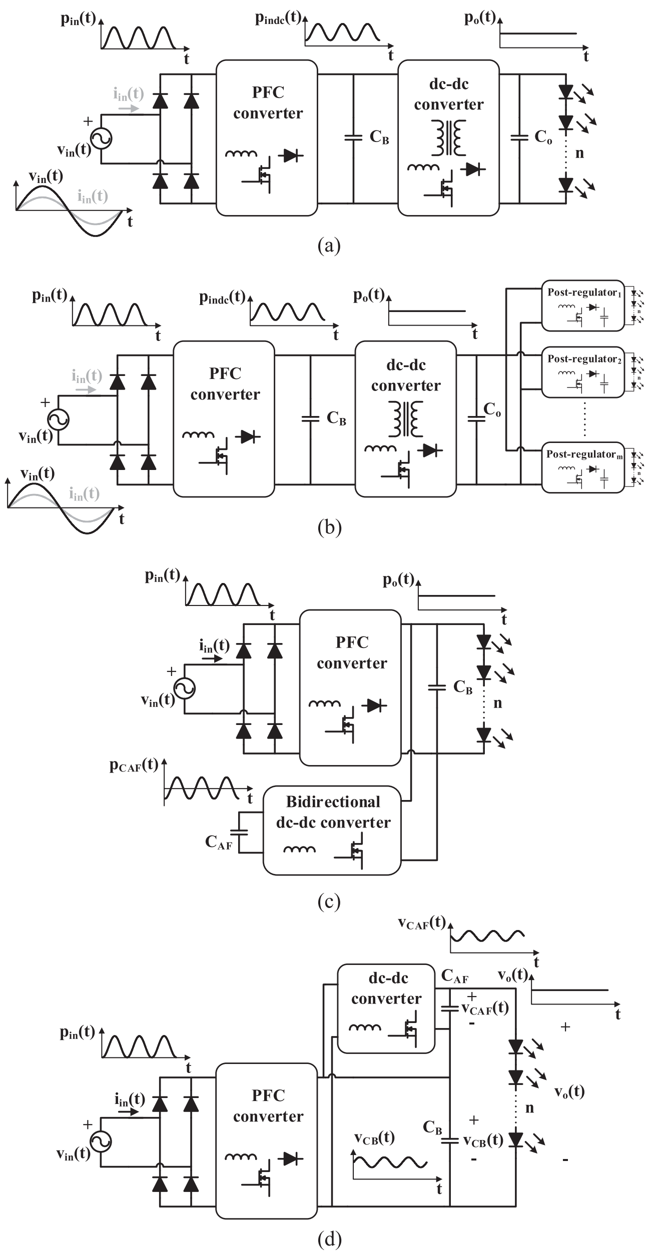


Fig. 13. Multi-stage solutions for LED drivers. (a) Two-stage solution (full cascade). (b) Two stage cascaded with a parallel input post-regulator configuration (full cascade). (c) Bidirectional dc–dc converter (active filter) [140]–[146]. (d) Multi-output voltage ripple cancellation (partial cascade) [147]–[155].

Although it can be done in the first stage by means of a flyback converter, this implementation suffers from low efficiencies and a bulkier capacitor due to the lower power density of low voltage capacitors in comparison to high voltage ones [156], [157]. Considering this fact, the inclusion of galvanic isolation is normally performed in the second stage. Other authors have proposed using an integrated single stage (i.e., bridgeless PFC + LLC) as the front end followed by simple dc–dc converters to regulate the LED strings [158]. This solution has a high component count but is able to ensure good light quality and current sharing while disposing of the electrolytic capacitor and having a high efficiency.

It is commonplace to think that a two-stage solution would be less efficient than the previously presented single-stage solutions. The reasons are the increased number of components and the double power conversion. Even so, the two-stage solution overall performance is better in terms of efficiency and reliability, due to the better optimization of its tasks in its two different stages. In addition, it may be able to remove the electrolytic capacitor [138].

Continuing on the proposals to remove the electrolytic capacitor, the last ones are those that fall into what can be considered quasi-single-stage ac–dc converters but are considered within the multi-stage category due to their addition of an extra stage. The reason for being considered quasi-single stage despite their inclusion of an extra stages comes from the fact that this extra stage does not process all the power as in the fully cascade solution of Fig. 13(a). Such are the ones that include a bidirectional dc–dc converter in parallel with the LEDs [140]–[146] or the ones based on multi-output ripple cancellation [147]–[155]. In the first scenario, see Fig. 13(c), the bidirectional converter handles the pulsating power [i.e., $p_{\mathrm{CAF}}(t)$] of C_B consequently diminishing its size. In addition, C_{AF} can have a reduced capacitance as its charge and discharge is done more efficiently in comparison to the grid pulsating power, and unlike the two-stage solution, the bidirectional converter does not process all the power. It should be noted that the parallel converter with a capacitor can be changed for a series converter with an equivalent inductance; however, the required inductance is much bulkier, thus it is avoided for ac–dc LED driver. A similar principle is applied in the multi-output voltage ripple cancellation solution in which a certain voltage ripple is allowed on C_B in order to reduce its size and value, which is compensated by the dc–dc converter responsible for cancelling it in order to drive the LED load with a dc current, see Fig. 13(d). For that reason, the output of the dc–dc converter will be a voltage waveform with its phase inverted from the output voltage of the PFC converter. The aforementioned quasi-single-stage solutions present high efficiencies at the cost of a complex control, high component count, and low bandwidth on the output current feedback loop. In fact, this complex control would require in some cases the use of digital control, which can also be seen as a drawback, as analog control is preferred for single-stage ac–dc LED drivers.

The aforementioned reasons make the use of two-stage solutions a reality for ac–dc LED drivers. However, as it has been mentioned before, the cost and complexity are the most limiting factors in most applications. Hence, these solutions are normally used for high performance luminaires (i.e., achieving full dimming and flicker free performances) in which reliability and efficiency are of utmost importance. In fact, ac–dc LED drivers occasionally add a cascaded extra stage, referred in previous literature as a post-regulator stage [159], see Fig. 13(b). The post-regulator is connected directly to the LED string, and the ac–dc LED driver would require, as many post-regulators as there are LED strings in the LED load, considering they are responsible for actively sharing the current between strings to ensure an adequate light output of the luminaire.

Along the summary of single-stage ac–dc LED drivers, different solutions to implement the PFC stage have been evaluated.

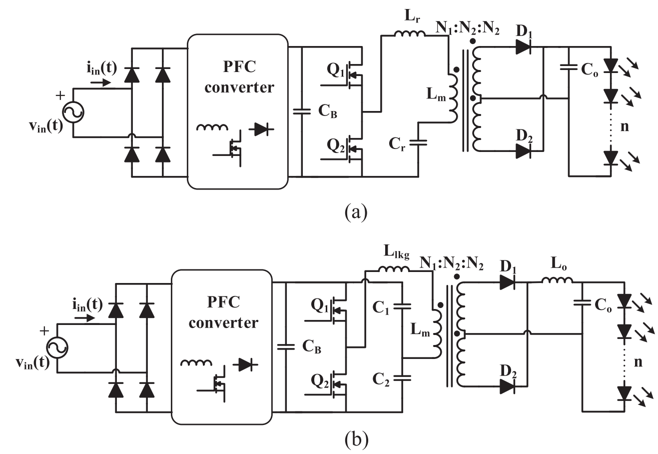


Fig. 14. Preferred solutions for the dc–dc isolated stage of a multi-stage ac–dc LED driver. (a) Half-bridge resonant LLC [171]–[180]. (b) Asymmetrical half-bridge (AHB) [165]–[169].

Particularly for multi-stage LED drivers, the most common topology is the PFC boost converter working in either continuous conduction mode (CCM) or boundary conduction mode (BCM) to achieve unity PF. The latest trends are focused on using its bridgeless variants to achieve higher efficiencies by removing the input diode bridge rectifier [161], [162], making the use of digital control mandatory. Nonetheless, its cost and complexity is justified in multi-stage solutions considering their aim for high reliability and performances, even though traditionally in PFC analog combo controllers have been used [163]. That being said, the focus of this section will be put on the other stages: the isolated dc–dc converter and the post-regulator.

Traditionally the second stage provides fast output voltage response and galvanic isolation. In the case of an LED load, the main characteristic that needs to be fulfilled by the second stage is the cancelling of the LF ripple of the PFC converter while achieving a high efficiency in order to remove the electrolytic capacitor. There is a limited spectrum of isolated solutions capable of this performance by means of a fast output feedback loop or a feed-forward input closed-loop, while guaranteeing a flicker free light output. In fact, there are two favored solutions over simpler ones, such as the flyback [164], for this particular application: the LLC resonant converter, that can be found either in its half-bridge, see Fig. 14(a), or full-bridge configuration, or the asymmetrical half-bridge (AHB), see Fig. 14(b).

In the case of the AHB, this topology is able to provide high reliability and high efficiency by reaching zero voltage switching (ZVS) in the primary switches [165]–[169]. In addition, the control scheme and the limited output voltage range required for the driving of LEDs allow a small design for its output filter. In fact, the low voltage range makes it possible to implement self-driving techniques when using synchronous rectification in the secondary side of the transformer [166]. On the contrary, the duty cycle range is limited to variations between 0 and 0.5, the potential bandwidth of its output feedback loop is limited due to the resonance that occurs between the input capacitors and the magnetizing inductance, and the dc gain is not linear. Some authors have proposed different techniques to overcome the bandwidth limitation to cancel the voltage ripple, such as the use of a feed-forward loop [166], [167]. Others have proposed the use of the Zeta AHB, which solves the two main disadvantages of the AHB, as are non-linear gain and the duty limitation [170].

The LLC resonant converter has been widely used for LED driving due to its high efficiency achieved by obtaining soft-switching in its main switches [171]–[180]. However, ZVS is achieved during the turn-ON on the primary switches and zero current switching is achieved on the diodes for singular conditions. These conditions limit the operating frequency to lower values than the resonant tank. Hence, when the load reduces the operating frequency will surpass that of the resonant tank, which means that the turn-OFF losses will increase. Some of the issues related to obtaining soft-switching conditions in this topology are improved for wider power ranges with the help of other resonant tanks [181]–[183].

According to the previous literature, the aforementioned second stages are able to remove the electrolytic capacitor without incurring in flicker, achieve high efficiencies (i.e., $> 97\%$), and perform total dimming. However, they are unable to ensure a correct light output in complex LED loads due to the lack of current control on each of the strings, unless a current sharing technique is used. Consequently, some current sharing techniques will be briefly detailed, even though they are unrelated to the achievement of a flicker-free ac–dc LED driver. In fact, for the scope of multi-stage solutions the implemented current sharing method needs to be extremely efficient. This statement discards the linear based regulator and the passive resistor current sharing techniques because of their low efficiencies, reducing the solutions to the use of a post-regulator per string [159], [184]–[189] or a pulsewidth modulation (PWM) dimmer per string [190], [191]. Another possibility is the integration of the post-regulator with the isolated dc–dc converter to reduce the cost and achieve active current sharing by means of multi-output converters [181], [186]. The issues with the integration come from the requirement of several HF transformers, which would make the ac–dc LED driver bulkier, and require a complex control to ensure the active current sharing. For this particular application, the buck converter is the preferred solution.

Among the newer trends that could be found in literature to reduce the cost of the second stage or the post-regulator is the driving of LEDs with HF pulsed current, also referred in literature as HF AC-LED. Unlike the LF AC-LED described within the passive solutions, the HF AC-LED does not incur in flicker due to the HF used. In fact, the difference with a PWM dimming pulsed current is using the switching frequency output current of a dc–dc converter by removing the output filter responsible for obtaining a dc current. This method has been applied to isolated dc–dc converters driving LEDs with an HF sinusoidal waveform [182], [192], [193], a flyback working in DCM with pulsed current driving the LED load with triangular waveform [194], [195], a self-oscillating driving the LEDs with a quasi-sinusoidal waveform [196], and conventional dc–dc converters where the LED is used as the rectifier diode of the converter [197]. Only Castro *et al.* [197] had empirically demonstrated the impact of pulsed current driving of LEDs on their lifetime, since they incur in some of the aforementioned

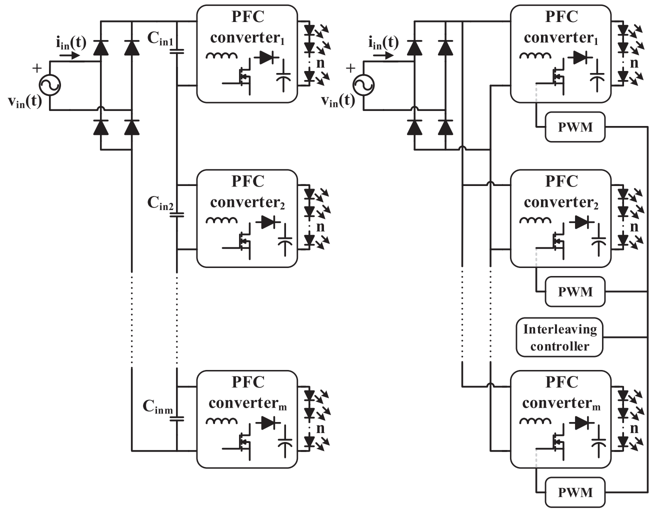


Fig. 15. Modular solutions for LED drivers. (a) Input-series [139]. (b) Input-parallel with interleaving [198]–[200].

cases in extremely high current peaks to achieve an adequate dc current level. Moreover, some of them require the duplication of the LED strings [182], [192], [193] not justifying the cost reduction, as the switching output current of the isolated dc–dc converter is required to be rectified.

4) Modular Solutions: Modular solutions are rarely used on ac–dc LED drivers due to the increased amount of components and complexity, potentially reducing the reliability of the driver. Nevertheless, some authors have studied solutions based on stacking several converters in series connected to the ac grid [139], see Fig. 15(a). This technique allows the use of cheaper and more efficient semiconductors due to the reduction of voltage and current withstood by them, but the overall power density is reduced due to the size limitation of the control stage, requiring another feedback loop to control the power demanded by each module. Furthermore, it is able to reduce the size of the output capacitor by stacking several capacitors; however, the removal of the electrolytic capacitor is not naturally achieved.

The other solution, which is well known in PFC, can be implemented with an input-parallel connection. The idea behind this solution is connecting several PFC converters in parallel at its input. The PWM signal controlling each module is phase shifted in such a manner that the sum of the input currents of each module reduces the HF ripple of the current of the ac–dc LED driver [86], [198]–[200], or reshaping the input current achieve a higher PF [201]. In addition, the LED load can also be independent for each module, see Fig. 15(b). In fact, the more converters there are, the lower the overall current ripple is. This method is referred in literature as interleaving and can be achieved both in open or closed loop with any ac–dc or dc–dc converter. Consequently, it is used with the ones that present significant input current ripples in order to reduce it, as those working in DCM or BCM [202], [203]. The main reason for using this technique is the reduction in size of the electromagnetic interference (EMI) filter, which grows larger with the input current ripple, affecting both the size and weight of the LED driver [204]. It should be noted that this technique does not impact the removal of the electrolytic capacitor and that the reduction of the EMI filter needs to consider the increased amount of components, as well as, the increase in size and control complexity of a modular solution.

Finally, Table III has been included to comprehensively summarize the most important facts among the discussed solutions for ac–dc LED drivers using generic topologies without delving into specific solutions. In addition several parameters of interest extracted directly from the analyzed references have been added, as are efficiency, PF, and THD. In the case of the efficiency, the solutions that have achieved the maximum and minimums efficiences are listed, as well as the average efficiency of all the analyzed solutions. As regards design parameters, such as the ability to operate in univeral voltage input range, the kind of controller used, and the ability to perform dimming, the solutions that have these benefits have been listed. It is important to note that as has been previously mentioned the ability for an ac–dc LED driver to comply with the flicker regulation will depend on whether it includes an output capacitor sufficiently large. For that matter, the flicker-free condition column summarizes which solutions are able to eliminate the electrolytic capacitor while keeping a flicker free performance. In fact, those solutions that achieve such feat are listed in their respective category.

IV. Three-Phase AC–DC LED Drivers

In this paper, it has been seen that the removal of the electrolytic capacitor is crucial to increase the lifetime of the ac–dc LED driver for it to be comparable to that of the LEDs. The reason behind its use is the pulsating power of the ac grid, which would result in a flicker effect on the light output of the LED load, which is both annoying and hazardous for human beings. This is not the case for a balanced three-phase ac power grid and all the required extra stages to remove said component can be disposed of. As outstanding as this is, there are two important limitations preventing three-phase ac–dc LED drivers from being massively used.

First, the lack of voltage standardization. Unlike single-phase power grids, in which the voltage is limited between 80 and 270 V, three-phase ac power grids show a wider range depending on the country and power of the grid. For low voltage three-phase ac power grids, the rms line-neutral voltage is nominally 347 V in Canada, 480 V in the USA [205], or 230 V in the European Union with the exception of the U.K. with 240 V. Although the proposal of a universal three-phase ac–dc LED driver seems complex and inefficient, it is not such a limiting factor to use regionally designed LED drivers, when the improvement in cost and simplicity is justified. In fact, considering the scope of power for medium to high-power luminaires (i.e., 50 W to 10 kW) the mobility requirement of universal PFC solutions can be completely disregarded.

And second, three-phase ac power grids are not as readily available as single phase ones. This fact reduces the applicability of this solution, since household ac–dc LED drivers represent most of the current LED driver market, and wiring three-phase ac power grids to household environments is costly for the

TABLE III
SUMMARY OF SINGLE-PHASE FLICKER-FREE AC–DC LED DRIVERS

	Advantages	Disadvantages	Efficiency (Min, AVG, Max) (%)	PF (%)	THD (%)	Universal input	Control	Dimming	Flicker-free condition
Passive [33]-[38], [40]-[45]	• Low component count. • Simplicity. • No control. • Compliance with Class D from the IEC 61000-3-2.	• Inability to control luminosity, unless extra circuitry is added. • No galvanic isolation. • Rated for less than 10 W • Extremely difficult to achieve a universal input voltage range solution.	80 [35], 88, 96.1 [36]	90-99	2-30	No	Only for dimming: - Analog: [33],[34],[37] - Digital: [35],[36],[38]	Yes, with extra circuitry	Require electrolytic capacitor.
Active: single-stage – < 25 W [46], [51], [52], [54]-[59], [76]-[84], [107], [195]	• Low component count. • Simplicity. • Ability to control the light output. • Any dc-dc converter can operate in this configuration. • Compliance with Class D from the IEC 61000-3-2. • Usage of analog controllers based on commercial ICs.	• No compliance with Class C from the IEC 61000-3-2. • No galvanic isolation: [54]-[59], [83], [84] • Difficult to remove the electrolytic capacitor without incurring in flicker.	55 [78], 84, 96 [195]	70-92	10-30	Yes. [51], [52], [55], [56], [76], [77], [79], [81], [83], [84], [107]	- Analog: [51], [52], [54]-[59], [76]-[84], [107], [195] - Digital: [46]	Yes. [56]-[58], [74], [76], [107], [195]	No electrolytic: [59], [76].
Active: single-stage – > 25 W [47]-[50], [53], [60], [73]-[75], [77], [108], [110]-[114], [136], [138], [196]	• Low component count. • Simplicity. • Ability to control the light output. • Sinusoidal input current. • Compliance with Class C from the IEC 61000-3-2.	• Difficult to remove the electrolytic capacitor without incurring in flicker. • Trade-off between capabilities (i.e., dimming, universal input, capacitor-less, etc.) • No galvanic isolation: [53], [64], [86]	67 [60], 89, 96 [53]	95-99	<10	Yes. [47]-[50], [73]-[75], [77], [111], [112], [114], [136]. [138]	-Analog: [47]-[50], [53], [60], [73]-[75], [77], [108], [110], [111], [113], [114], [138], [196] -Digital: [64], [136], [112]	Yes. [49], [64], [73]-[75], [77], [108], [110]-[114], [136], [138].	No electrolytic: [47], [48].
Active: integrated single stage [64], [85], [88], [89], [91]-[105], [119], [121]-[133]	• Ability to control the light output. • Sinusoidal input current. • Wide input power range. Typically used for more than 25 W. • High power density. • Compliance with Class C from the IEC 61000-3-2.	• High stress on the main switches. • Complex control. • Difficult to achieve universal voltage range. • Lacks control on the intermediate bus voltage. • Trade-off between capabilities (i.e., dimming, universal input, capacitor-less, etc.) • No galvanic isolation: [95], [97], [100], [119], [123]-[125], [127], [131]-[133]	73 [129], 88, 95 [102]	93-99	< 20	Yes. [89], [91], [98], [103], [129]	-Analog: [64], [85], [88], [89], [92]-[94], [96], [102]-[105], [119], [121]-[130], [132],[133] -Digital: [91], [95], [97], [131]	Yes. [88], [92], [98], [99], [101]-[105], [121], [123]-[125], [127]-[132]	No electrolytic: [88], [99], [101], [121], [124], [131], [132]
Active: multi-stage – full cascade [157]-[159], [161], [163]-[184], [186]-[190], [192], [193]	• Ability to control the light output. • Sinusoidal input current. • High efficiency. • Reliability. • Galvanic isolation. • Universal input voltage range • Compliance with Class C from the IEC 61000-3-2.	• Typically used for more than 100 W. • Favors the use of digital or analog-digital controls. • High component count.	86 [159], 92, 95 [158], [169], [183]	99	<10	Yes. [159], [161], [163]-[184], [186]-[190], [192], [193]	- Analog: [157]-[159], [164], [169], [173], [174] - Digital: [163], [165]-[167], [170], [172], [175]-[183], [189], [192], [193] - Mixed: [183], [186], [187]	Yes. [157]-[159], [161], [163]-[184], [186]-[190], [192], [193]	No electrolytic: [157]-[159], [163], [166], [167], [169], [170], [175], [177]-[180]
Active: multi-stage – partial cascade [147]-[155]	• Ability to control the light output. • Sinusoidal input current. • High efficiency. • Extra stage does not process all the power.	• Input power of more than 25 W. • High component count. • Problematic in case of output short-circuit. • No galvanic isolation: [147]	85 [155], 91.5, 98 [153], [154]	97-99	<15	Yes. [147], [150]-[155]	- Analog: [147]-[155]	Yes. [151], [154]	No electrolytic: [148]-[150], [152]-[154]
Active: multi-stage – active filter [140]-[146]	• Ability to control the light output. • Sinusoidal input current. • Extra stage does not process all the power.	• Input power of more than 25 W. • High component count. • High control complexity. • Extra storage element required • No galvanic isolation: [145].	80 [142], 85, 90 [145]	94-99	<10	Yes. [140], [141], [143], [144]	- Analog: [140], [143], [144] - Digital: [142], [145], [146]	Yes. [140], [146]	No electrolytic: [140]-[146]
Modular [86], [139], [198]-[201]	• Ability to control the light output. • Sinusoidal input current. • Extra benefits (lower THD, independent LED loads, etc) • High efficiency.	• Input power of more than 25 W. • High control complexity. • Very high component count, due to the multiple modules required. • No galvanic isolation: [139], [201]	91 [198], 92, 94 [86], [139]	99	<10	Yes. [198], [201]	- Analog: [86], [198] - Digital: [139], [201]	Yes. [86], [139], [201]	No electrolytic: [139]

benefits obtained. Therefore, three-phase ac–dc LED drivers are proposed for those places where the three-phase ac power grid is accessible, such as, commercial and industrial installations. The application can then be focused on high-power luminaires, tunnel lights, stadium spotlights, floodlights, etc. Particularly, for those luminaires of more than 250 W that require high reliability and efficiency.

These two reasons are keys to understand the most common way used nowadays to drive LEDs in three-phase ac power grids. The method is based on using an LF step-down autotransformer connecting it between line and neutral to adjust the voltage to that of a single-stage ac–dc LED driver [206]. This methodology requires access to neutral, limiting the use of this solution to 4-wire grids. It also reduces the efficiency of the

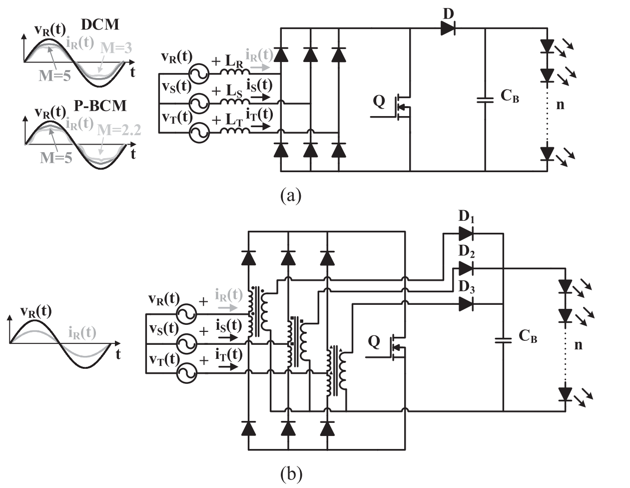


Fig. 16. Single-switch three-phase ac–dc solutions for LED drivers. (a) Boost converter. (b) Flyback converter [208].

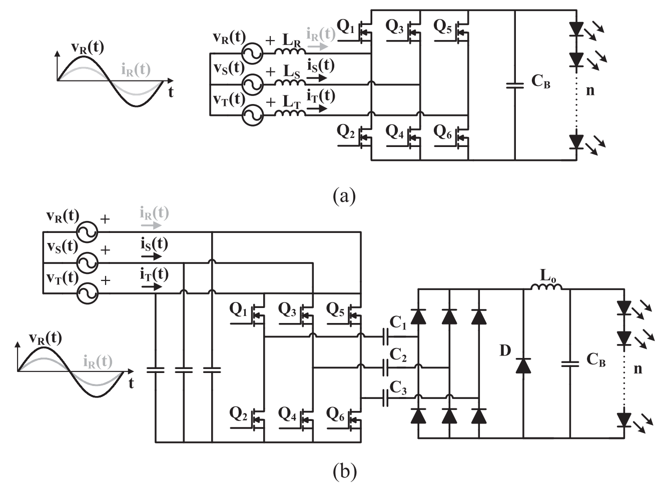


Fig. 17. Multi-switch three-phase ac–dc solutions for LED drivers. (a) Boost converter. (b) Resonant switched capacitor LED driver [209].

system greatly due to the losses on the autotransformer, which can achieve in the best case 95% efficiency. Furthermore, the most important aspect is the increase in size and weight that an LF autotransformer does to the whole system [207].

In order to solve the aforementioned issues the use of specific three-phase ac–dc converters to drive LED loads increasing both efficiency and power density, while guaranteeing non-flicker performance have been proposed [208], [209]. This section will focus on the most promising solutions for LED driving based on three-phase ac–dc considering the lack of previous literature on the topic.

A. Single Stage

Following the same principle introduced for single-phase ac–dc single-stage solutions, the aim would be to comply with Class C from IEC 61000-3-2, which as a reminder is the most restrictive of the two harmonic injection regulations that a three-phase ac–dc LED driver will need to comply with, being the other Class A from IEC 61000-3-2. Hence, the studied solutions would require sinusoidal input current waveforms in phase with their respective phase voltage. These topologies can be further divided into single-switch and multi-switch categories in accordance to the amount of active switches used. The first ones are the most attractive for LED drivers in terms of cost and reliability. Among these solutions there are two that stand out from the rest, as are the three-phase ac–dc single-switch boost converter, see Fig. 16(a), and the three-phase ac–dc single-switch flyback converter, see Fig. 16(b).

The three-phase ac–dc single-switch boost converter is able to achieve a quasi-LFR performance in DCM or in pseudo-BCM depending on the gain of converter (M) [210]–[215]. In fact, the higher the converter gain, the lower the THD, requiring at least a gain of 3 and 2.2 to ensure the compliance with Class C from the IEC 61000-3-2 in DCM and pseudo-BCM, respectively. In this particular case, the LED load will be withstanding high voltages (i.e., a minimum of 1 kV for DCM and 800 V for pseudo-BCM under the European input voltage standard). Nonetheless, this task can be alleviated with the latest technology of HV LEDs. Moreover, due to the high voltage bus the main switch will incur into higher switching losses and soft-switching will become necessary to achieve an efficient solution. Some authors have proposed the use of passive filtering the input current to achieve lower bus voltages and lower THDs at the cost of increasing weight and size, which is undesirable for an LED driver [214].

In a similar fashion, a dc–dc flyback converter can be connected to a three-phase rectifier, by doing so, galvanic isolation is achieved. However, the LFR performance of the flyback in this configuration will make the input currents of each phase not to be ideally sinusoidal since the conduction angle is 120°, thus not complying with the aforementioned harmonic regulation. In order to solve this issue, an LFR performance needs to be achieved per phase. For that matter, some authors have proposed the three-phase ac–dc single-switch flyback converter, see Fig. 16(b), in which a coupled inductor with two input windings is used for each phase. The upper winding conducts during the positive half-line cycle of the voltage phase and the lower winding during the negative one [216], [217]. Accordingly, the operation of the driver is equivalent to the use of a flyback per phase achieving the desired operation. However, its PF roughly reaches 0.9 for the higher voltages of the European three-phase ac power grid, its efficiency is well below the desired 90% for an ac–dc LED driver, the design tolerances of the coupled inductances can severely affect the current ripple on the LED load, and the main switch needs to withstand high voltages and currents [208]. These characteristics make this driver unfitting for luminaires of more than 200 W, which is the desired range of power for LED spotlights. Furthermore, the importance of galvanic isolation introduced for single-phase ac dc LED drivers to meet the safety requirements, becomes inconsequential for their three-phase counterpart considering the aim for high-power luminaires in inaccessible places, which only authorized personnel should have access to.

Taking into account this last statement and in search of more efficient ac–dc LED drivers, multi-switch ac–dc three phase can be considered into this study. Consequently, the simplest topology that can achieve unity PF is the multi-switch boost converter, see Fig. 17(a) [218]–[221]. In fact, this topology achieves lower voltages on the output bus than the single-switch one previously introduced while keeping a sinusoidal input current. The condition to achieve unity PF requires the output voltage to be greater than the output dc voltage attained by the six diode rectifier bridge formed by the parasitic diodes of each MOSFET. It should be noted that the control is more complex than single-switch solutions and that its bidirectionality is not leveraged for LED applications.

Continuing the analysis, some authors have tackled the design of three-phase multi-switch ac–dc LED drivers by means of switched capacitor converters, see Fig. 17(b) [209]. These ac–dc LED drivers can achieve high power density, high efficiency, do not require current sensing to maintain a stable light, and can have lower output voltages. In contrast, the proposal requires variable frequency operation, controls the voltage withstood by the LED load instead of its current, cannot achieve full dimming condition and require several active switches and diodes, which will hinder its reliability.

B. Multi-Stage

Another possibility to attain input sinusoidal waveforms is the use of multi-stage solutions. Unlike single-phase ac–dc multi-stage solutions, in which the isolated dc–dc converter could remove the LF ripple across the LED load, three-phase ac–dc LED drivers can naturally remove the LF ripple with a single stage, hence, disposing the electrolytic capacitor due to the non-pulsation of the power grid on the load. Therefore, the actual use of this second stage would be focused on adapting the voltage and current levels to those required by the LED load and provide galvanic isolation. For that matter, the purpose of the second stage is closer to the post-regulator or third stage of the single-phase ac–dc multi-stage scheme. The topologies normally used for the second stage are similarly based on the ones introduced for the single-phase multi-stage LED drivers due to the requirement of a high step-down gain [222], [223] (i.e., LLC or AHB).

In regard to the first stage, it is traditionally comprised of the three-phase multi-switch ac–dc boost previously introduced, because of its higher efficiency and its ability to achieve PFC. This higher efficiency becomes necessary in order to be able to compete with single-stage-based solutions as the two stages will hinder the efficiency of the three-phase ac–dc LED driver. However, one of the main advantages, which is bidirectionality, will not be leveraged with an LED load. In addition, the increased amount of components, which increment cost and diminish reliability, the arguably lower efficiency of the whole driver and the lack of purpose of the second stage responsible for removing the electrolytic capacitor in the single-phase scenario, have made the use of three-phase multi-stage ac–dc LED drivers unattractive.

C. Multi-Cell Solutions

One of the simplest ways in which a three-phase rectifier can be developed was proposed by Delco as a three-phase rectifier using thyristors as the main switches for a resistive load [224]. The approach is based on having several ac–dc converters with PFC (i.e., PFC converters), which will be defined as cells, each connected to a phase and working as an LFR, see Fig. 18. These

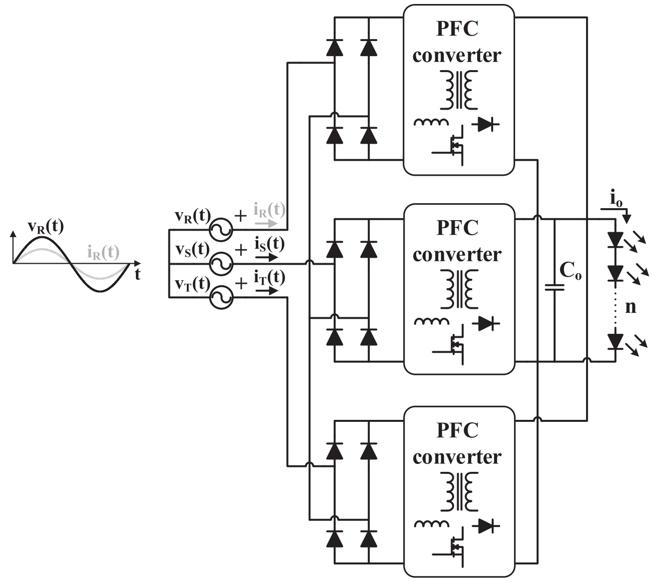


Fig. 18. Delco ac–dc LED driver [225].

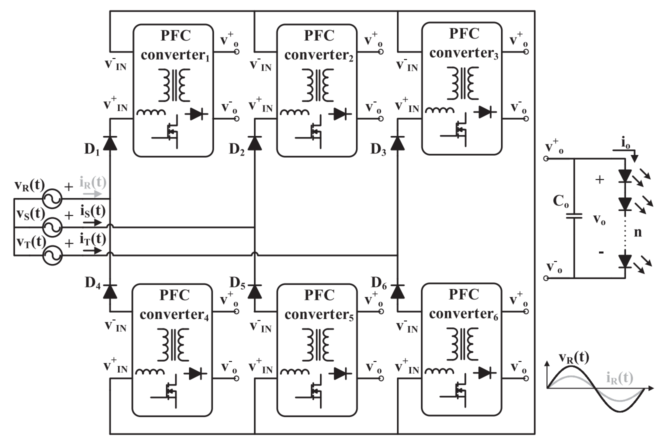


Fig. 19. Multi-cell ac–dc LED driver based on the three-phase full-wave rectifier [225], [226].

ac–dc converters require galvanic isolation in order to be able to connect their outputs in parallel. By doing so, the electrolytic capacitor can be removed as there is no actual pulsation of power on the load. However, this reduces the potential topologies that can be used for this task.

The Delco topology was proposed as a three-phase ac–dc LED driver in [225] where it was compared to the multi-cell ac–dc LED driver based on the three-phase rectifier [225], [226], see Fig. 19. The study shows that both topologies comply with the required regulations and recommendations while disposing of the electrolytic capacitor. In addition, the comparison shows that the multi-cell ac–dc LED driver based on the three-phase full-wave rectifier performs better in terms of efficiency at the cost of having an increased number of cells and components. Nonetheless, their efficiency is still low, as it barely reaches 90%, which actually happens due to the implementation of the cells with flyback dc–dc converters.

Moreover, the design of each module is equivalent to that of a single-phase ac–dc converter with PFC, which simplifies and improves the power scaling of the ac–dc LED driver, considering

TABLE IV
SUMMARY OF THREE-PHASE FLICKER-FREE AC–DC LED DRIVERS

	Advantages	Disadvantages	Efficiency (%)	PF (%)	THD (%)	Universal input	Control	Dimming	Flicker-free condition
Single-stage: Single-switch [208]	• Low component count. • Simplicity. • Galvanic isolation.	• High stress on the main switch. • May require a high output voltage to sustain a sinusoidal input current. • Very low efficiency. • It would require an extra stage for current sharing.	75[208]	99	7	No	Analog	Yes	Electrolytic capacitor removed
Single-stage: Multi-switch [209]	• Compact. • High efficiency.	• High component count. • Complex control. • It would require an extra stage to ensure current sharing. • No galvanic isolation.	91[209]	99	4	No	Analog	Yes	Electrolytic capacitor removed
Multi-stage	• High efficiency. • Traditional first stage. • Galvanic isolation.	• Very high component count. • Second stage is merely used to adequate voltage and current levels to the LED load.	-	-	-	-	-	-	Electrolytic capacitor removed
Mutli.cell: Traditional [225],[226]	• Modular. • Scalability. • Galvanic isolation.	• Very high component count. • Reduced amount of topologies, as galvanic isolation is mandatory and they also need to operate as LFRs. • Complex control. • Cell tolerances.	88[225], 90[226]	99	5	No	Digital	Yes	Electrolytic capacitor removed
Multi-cell: Light summing [232],[233]	• Modular. • Scalability. • Any LFR can be used as the cell of this topology. • Very high efficiency.	• Very high component count. • The LED load needs to be correctly positioned to ensure flicker-free operation. • Very high component count. • Complex control. • Cell tolerances. • May require HV LEDs	97.5[232], [233]	99	7	No	Digital	Yes	Electrolytic capacitor removed

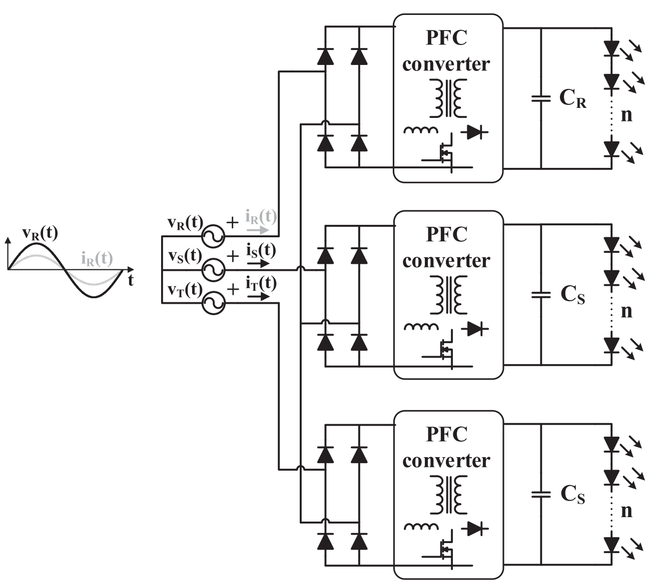


Fig. 20. Multi-cell ac–dc LED driver based on summing the light output of each phase [232], [233].

the modularity of the solution. As has been mentioned before, an LFR performance is required to attain PFC, particularly for this case with galvanic isolation. Therefore, the simplest way to achieve this performance is by means of an isolated topology from the buck-boost family working in DCM. For that matter, some authors have proposed to use the following topologies as cells, the flyback converter [227], [228], the Ćuk converter [229], or the SEPIC converter [230]. The issue being the same one introduced before regarding the low efficiencies achieved by these converters in comparison with a two-stage solution. Therefore, it is also possible as introduced by other authors, the use of a two-stage cell approach in order to achieve higher efficiencies [231], or any of the quasi-single-stages introduced in Section III-B1. In contrast, the control and amount of components included in this solution increases dramatically, becoming of interest for high-power luminaires (i.e., > 1 kW).

In order to improve the efficiency, the multi-cell ac–dc LED driver based on summing the light output of each phase has been proposed in [232], see Fig. 20. The proposal is based on using a highly efficient cell without an electrolytic capacitor, disregarding whether it provides galvanic isolation or not, and connecting an LED load directly to each cell. The total light output of this ac–dc LED driver would be constant, being the sum of lights of each phase, which is a method that was used during the Beijing 2008 Summer Olympics in the National Stadium, also known as Bird's nest, with several spotlights each of 1.5 kW and 125 000 lm [234]. In addition, the work presented in [232] is able to achieve a high efficiency, comply the regulations, and achieve a very low Mod. (%), at the cost of having to correctly position the LED loads to adequately blend the light output and having an increased LF ripple across the LED loads.

These multi-cell approaches are more complex from a control point of view since they add more components and are arguably more expensive than the three-phase single-switch single-stage ac–dc LED drivers, which typically require the use of a central control unit. This central control unit will be responsible for ensuring that each of the modules processes the same amount of power and that correctly starts-up, normally requiring digital control for this purpose. In contrast, they have a better tradeoff between output voltage and THD than the aforementioned three-phase single-switch single-stage ac–dc LED drivers.

In a similar fashion to what was done for single-phase ac–dc LED drivers, Table IV summarizes the advantages and disadvantages of the several three-phase ac–dc LED drivers that have been discussed, as well as, listing the achievements and design parameters. In this particular case, it can be easily seen that the biggest advantages is the straight removal of the electrolytic capacitor. It should be noted, that these considerations are made in a general way and specific solutions may have additional advantages and disadvantages.

V. Conclusion

A comprehensive and generalized review of ac–dc LED drivers have been carried out taking into account the latest trends and considering the specific regulations and recommendations that ac–dc LED drivers need to comply with, nowadays. This review has led to classify ac–dc LED drivers into two major categories depending on which ac power grid they are connected to: single phase or three phase. From these two major categories, the ac–dc LED drivers are then classified into four minor categories for single phase and three for three phase taking into consideration the amount of power stages used. These categories that are discussed throughout the review are summarized into Tables III and IV, for the designer to understand the advantages and disadvantages of state-of-the-art ac–dc LED drivers and see at a glance the benefits of each of the categories and solutions.

The aim of the publications on the topic of flicker-free ac–dc LED drivers can be typically summarized on increasing the efficiency, reducing the cost, and removing the most limiting component in terms of lifetime, which is the electrolytic capacitor. Particularly for LED lamps (i.e., < 25 W) in single-phase ac power grids, the use of passive solutions has been widespread with only a handful of works carried out for active solutions where the aim is a single stage without an electrolytic capacitor. However, the simplicity and cost efficiency of passive ac–dc LED drivers makes them overall a more attractive solution for LED lamps. In contrast, for LED luminaires (i.e., > 25 W) in single-phase ac power grids that require a much restrictive regulation, the achievement of dimming, a high light quality, a high efficiency, galvanic isolation, a flicker-free performance, and the removal of the electrolytic capacitor are almost mandatory, leading to consider apart from quasi-single-stage, the traditional two stage or even multi-stage approach. However, only the latter is able to achieve all those benefits within an LED driver, whereas most of the quasi-single-stages require to tradeoff some of them.

Considering the ubiquity of LEDs among lighting products and the aim for high-power luminaires, a handful of works have been developed around three-phase ac–dc LED drivers for commercial and industrial installations. In this particular case, the removal of the electrolytic capacitor becomes immediate, but at the cost of attaining a more complex ac–dc LED driver, which needs to achieve a high efficiency due to the power consumed by the luminaire (i.e., > 250 W). For low and medium power ranges, the use of single-switch solutions is the simplest solution, disregarding the fact that a current sharing technique will be required. As regards, high-power LED luminaires multi-switch and multi-cell topologies become more atractive due to their higher efficiencies, and their ability to process more power. Particularly, multi-cell topologies due to their scalibility, as they are able to add as many optimized cells or modules as required. However, they would still require the use of a current sharing technique to ensure that the same current goes across all the LED strings of the LED load, unless a multi-cell ac–dc LED driver based on light summing is used, whose cells also perform as the post-regulator stage.

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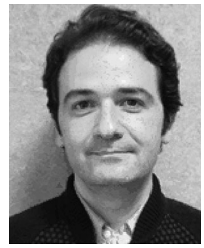

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