“Reliable and cost effective LED drivers improving perception artefacts and grid compatibility”

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Besides cost, size and basic functionality LED drivers distinguish in their quality of voltages and currents. On the LED side this relates to the light quality, especially flicker. On the grid side, the current shape must match limits for higher harmonics and power factor according to standards.
Based on a survey on over 1400 commercial LED drivers and the literature review, a range of LED driver topologies are classified according to their applications, power ratings, performance and their energy storage and regulatory requirements. Both, passive and active LED drivers are included in the review and their advantages and disadvantages are discussed.

1. Introduction

Light-emitting-diodes (LED) are gaining acceptance in the lighting market and replacing traditional lighting sources in a growing list of decorative, display and public lighting applications. [2][3][4][5][6]. Unlike incandescent and discharge lamps, LEDs are semiconductor devices that are highly sensitive to electrical, thermal, and photonic variations. LED systems should be properly designed and operated [2][3][7][8][9][10][11][12], in order to fully utilize their potential benefits.
LED systems should be designed to meet the technical specifications within practical constraints such as costs, form factors, reliability and international regulations such as the Energy Star Program and IEC Standards [13][14]. In this regard, an appropriate choice of an LED driver to suit a particular application is essential. Since most of the LED drivers are based on the switched mode power converter topologies previously developed as voltage sources, it is necessary to consider the suitable circuit topologies that can be used as current sources for LED applications.
Based on a survey on over 1400 commercial LED drivers with the Digikey system [15] in September 2014 and a literature review, a range of LED driver topologies are classified according to their applications, power ratings, performance and their energy storage and regulatory requirements. Both, passive and active LED drivers are included in the review and their advantages and disadvantages are discussed. This publication is based on a previous paper [1], from where several parts are taken over and further insights are added. It is supported by the Theme-based Research Scheme (T22-715/12-N) of the Research Grant Council of Hong Kong.

2. Existing LED drivers

Based on the survey on existing commercial LED drivers, the distributions of these products according to their power ratings, output voltage ratings, and price are reviewed. These distributions reflect the existing market needs and different requirements for different applications. Such distributions are expected to continue to expand as LED products enter new lighting markets.
The power range of the LED drivers can be broadly divided into three groups, namely low power (<25W), medium power ((25W-100W) and high power (>100W). LED drivers with a power rating of more than 25 W typically provide galvanic isolation. In the low power range the picture is less clear: Depending on the application some provide galvanic isolation, while others don’t.

2.1. Output Voltage Ratings

The ratings of the output direct current (DC) voltage and current are important factors that affect the selection of the LED driver topologies. LEDs can be arranged in series or parallel, or a combination of both. LED system designs become even more diverse because of the vast variety of LED devices with different voltage and current ratings available in the market. Based on the data obtained in the survey, the distributions of the output voltage against the power ratings of the 1462 LED products from 3 W to 300 W are displayed with a logarithmic scale in Figure 1. (*Note*: some data are identical and are overlapped in Figure 1.) As a result, the following observations can be made:

- The output voltage and system power levels among LED products are diverse. Such diversities are due to the vast variety of LED products and also a lack of international standards. This situation is in contrast with traditional lighting systems such as incandescent and discharge lamps that have standardized discrete lamp voltage and system power levels.
- The data points cover a triangular area on the 2-dim plane of output voltage versus power rating, as shown in Figure 1. The points lying on the upper boundary line correspond to LED samples having the maximum rated current value, and each point has the same rated current which is equal to 0.35 A.
- The output voltage of most of the LED products in the low power sector is kept within 50V primarily because of the low power requirements. For medium and high power products, the range of the output voltage is wide. It is noted that a fairly large number of products of the medium and high power sectors also adopt an output dc voltage below 50 V. The choice of such output voltage is application dependent. For display applications, low-voltage and parallel LED strings are commonly adopted. For high power street lighting, a high output voltage with single LED string can reduce circuit complexity. Safety is also a major factor for the choice of using low dc voltage. According to the Low Voltage Directive 2006/95/EC, which is mandatory required for the CE Mark scheme [16], the safe operating voltage for human is below 50 V. Designing the output voltage at lower than 50 V can simplify the fixture and electronic designs of the LED system without the special need for electrical isolation. This helps to reduce system cost and size.

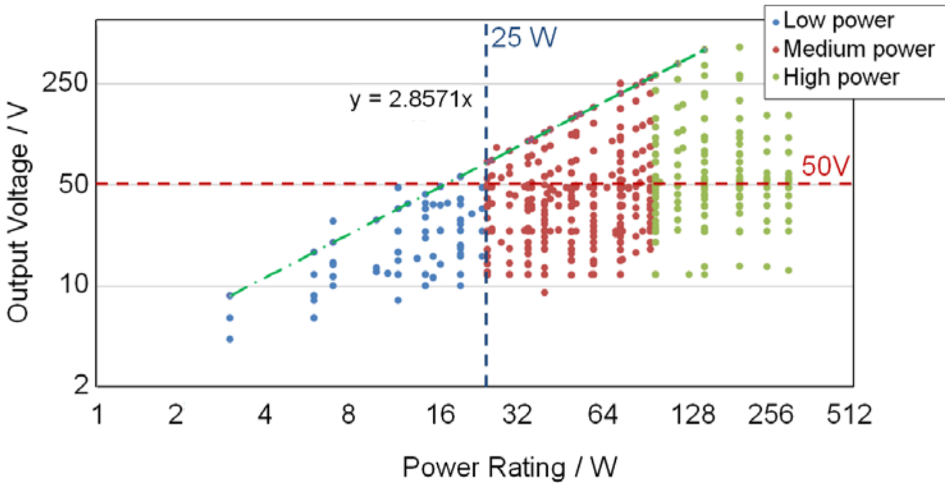

Figure 1: Output voltage of investigated LED drivers as a function of the rated power.

2.2. Prices and cost challenge

In general, the retail price increases with the power level in the low and medium power sectors, and tends to saturate at high power level. Figure 2 shows the prices related to the rated power as US dollar per Watt. It is noted that such US$/W decreases with increasing power level. It changes from 4.6 US$/W in the low power sector to 0.5 US$/W for the high power sector. The trend provides an explanation for the price saturation in the high power level.

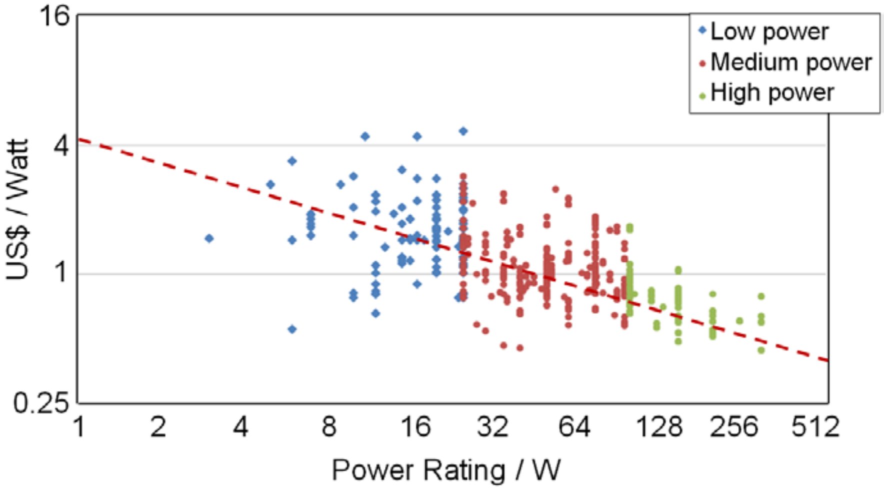

Figure 2: *Prices of the investigated LED drivers as a function of the output power. The red line represents an approximation of the trend.*

The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) program has published the LED luminaire cost, of which the driver constitutes 10% to 20% of the total manufacturing cost [17]. It is suggested that the cost of LED systems be reduced by 70% every four years [17], as shown in Figure 3. The expected price reduction applies to all components more or less equally.

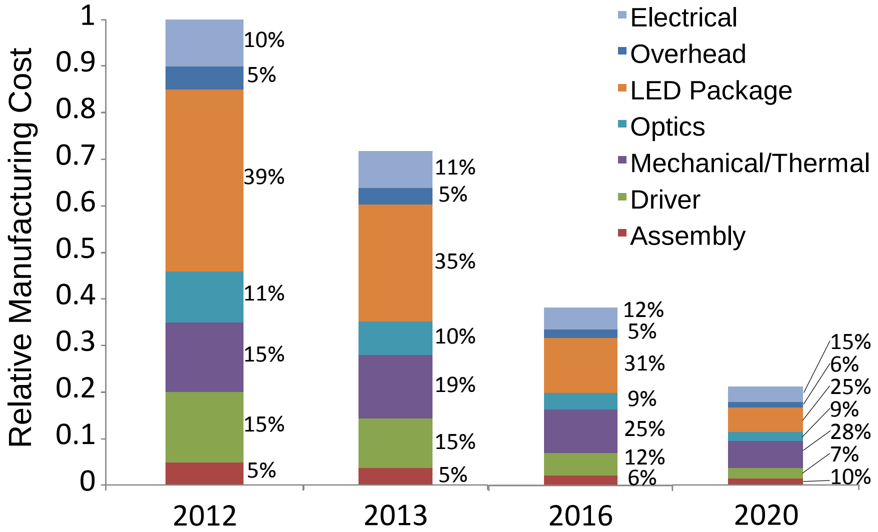

Figure 3: *Suggested cost reduction targets for a typical A19 Replacement Lamp. Extracted from [17]. Source: DOE SSL Roundtable and Workshop attendees*

3. Design Challenges

The selection of a suitable circuit topology is crucial to achieve a low overall system cost. Whichever topology is selected, its basic role is to meet the technical specifications including international regulations, such as achieving a good power factor (PF) and low total harmonic distortion (THD), while maintaining high efficient power conversion and complying regulations (The Energy Star program and IEC standard are most widely adopted for (SSL) luminaires) with respect to electrical, thermal, safety, warranty aspects. A survey of the international standards for a range of technical requirements is included in [1]. Furthermore, the quality of the light output is a design criterion.

Figure 4 gives a qualitative illustration on the relationship between power level, the associated PF requirement, and the expected system cost and complexity of the driver circuit. As low power applications have less stringent requirements, lower cost is desired. For medium and high power applications, high quality PF and THD must be guaranteed with a higher expected cost. But this

also means that in terms of achieving low cost/watt, it is more challenging to design an LED driver for the low power applications than for medium and high power ones.
Another challenge in LED driver design is to meet all the above requirements simultaneously within the product form factor. For high power class applications such as street lighting, space is usually less critical. However, most indoor applications (low and medium power classes) have limited space and require compact designs.

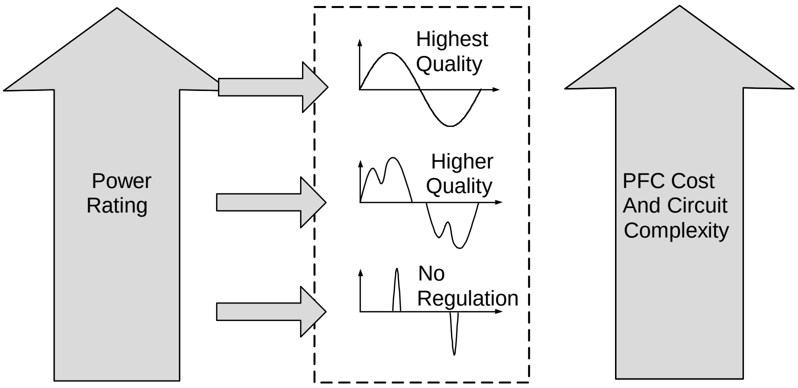

Figure 4: Comparison of power factor quality, power rating and cost of a typical LED driver.

4. Passive LED driver

Passive drivers comprise only passive components like e.g. resistor, capacitor, magnetic components (e.g. inductor/ transformer) and diodes, and are operated at line or double-line frequency. Passive drivers are known to be more reliable, because passive components are less sensitive to disturbances than active components and most of them have a longer lifetime.
The simplest passive drivers are resistive drivers with a transformer adapting the line voltage and a rectifier to convert the AC voltage into DC. An elcap would be used to smooth the DC voltage in order to avoid flickering. Such a driver is not preferred, because the resistor generates unwanted losses and the input current is not sinusoidal due to the elcap. In addition the elcap limits the lifetime, because it may dry out.
Preferred are drivers, where the current limiting resistor is replaced by an (ideally) lossless inductor, as listed in [1] as examples. As a disadvantage, such inductors are bulky. But if size doesn’t matter, such circuits may be highly reliable. Especially for street lighting, this is the case. In fact, in South China, where lightnings exceeding 10000 times per day in the summer is not uncommon, and in North China, where extreme low temperature persists in the winter, such a reliable circuit is needed. Therefore the generic topologies have been further developed and in [18] a driver for such an application is presented. Figure 5 shows its circuit diagram. Details are explained in [18]. The input inductor L_S limits the input current and provides PFC function. The parallel capacitor C_S provides reactive power compensation. The valley fill circuit allows reducing the capacity of the capacitors such that elcaps can be omitted. This improves the lifetime considerably. The output inductor L_{filter} flattens the output current to avoid flickering of the LED. In order to limit the size of the output inductor, a remaining ripple is left. However, this electrical ripple is further reduced as optical ripple making use of the luminous flux characteristic as shown in Figure 6. The light output of a LED goes into saturation above a certain power level and even reduces, if the electrical power is further increased. This is mainly caused by thermal effects. Operating around the peak luminous output allows affording an electric ripple ΔP_{LED} with minimized luminous ripple $\Delta\phi_V$ as illustrated in Figure 6.
The components of a demonstrator circuit for a typical street lamp of 63 W LED power as presented in [18] are shown in Figure 7. Despite their bulky size and heavy weight solely attributed by the large inductor required in the circuit, it offers superior reliability since they comprise no active switch, gate drives, integrated circuits and controllers, external power supplies, and elcaps. In fact,

the patented passive driver has reached the production stage for street lighting applications in China [18].

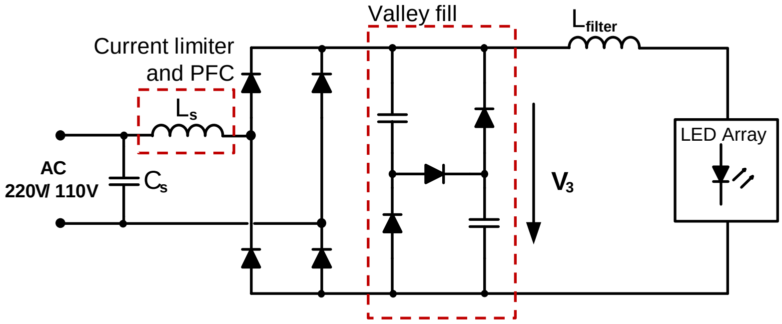

Figure 5: Circuit topology of the passive LED driver for street lighting [18].

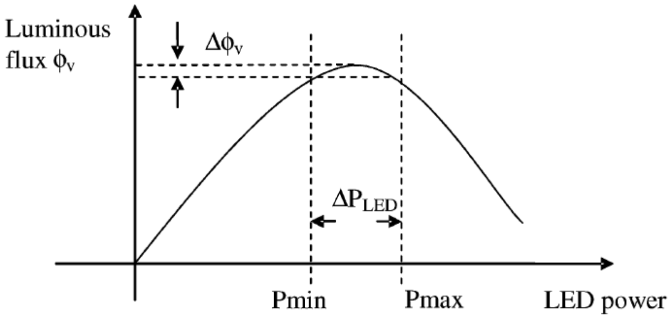

Figure 6: Avoiding flicker by making use of the luminous flux curve of an LED [18].

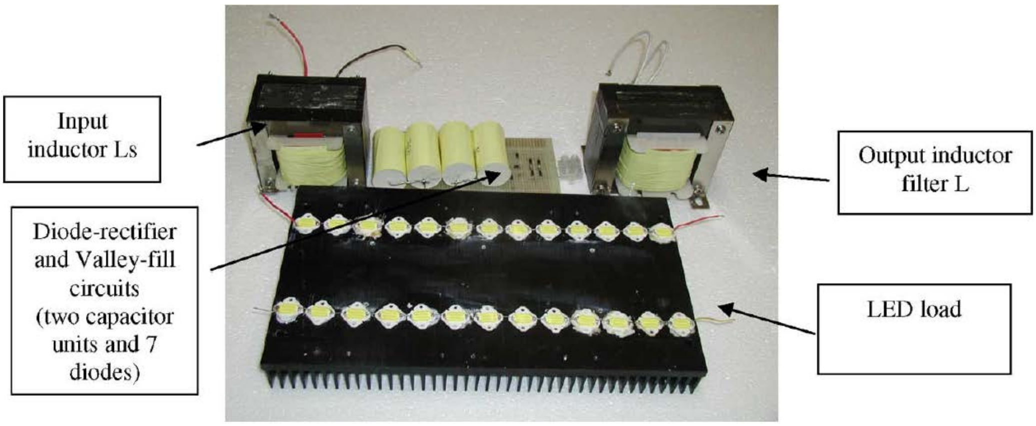

Figure 7: Components of the demonstrator circuit of the passive LED driver for street lighting [18].

5. Active LED drivers

Recently, a vast variety of switched-mode LED driver topologies has been proposed. According to the power processing stages, these topologies are classified as single stage (S1), two stages (S2), and three stages (S3), regardless of the presence of galvanic isolation in the converters. S1 and S2 drivers are discussed here.

5.1. Single stage drivers

Switched-mode single-stage (S1) drivers have only one power conversion stage and are the simplest circuit structure with the fewest number of power components. Consequently, they are of low cost and component count. However, it is often difficult for S1 drivers to ensure good performance, such as high efficiency, good PF, and constant current output simultaneously, since these functions have to be performed through only one power processing stage.

Depending on the location of the storage capacitor, S1 driver can be further sub-classified into Type A and Type B (see Figure 8a and b).

The type A (S1A) driver has its storage capacitor $C_{storage}$ directly connected on the low frequency side. One merit of the S1A driver is that its output can be designed to exhibit small voltage and/or current ripple. However, its pulsating input current (shown as I_{line}) is the main drawbacks of S1A drivers. S1A drivers are only applicable to very low power applications, typically below 5 W [19][20].

In Type B (S1B) drivers, the capacitor is placed on the high-frequency side after the DC/DC converter, as illustrated in Figure 8b. Here, the single DC/DC converter is operated to achieve both PF correction and output current regulation simultaneously. Thus, the input current waveform of S1B drivers is better shaped than that of S1A drivers. This property makes S1B drivers preferable to S1A drivers in low power applications. However, the required storage capacitance is not reduced as it has to handle both the high-frequency switching ripple and the low-frequency ripple. Therefore, S1B drivers inevitably contain low-frequency output current ripple. In general, a capacitance per power rating value of 1 µF/W is a very common value for DC-link capacitors in such PFC converters [21][22]. There are different topologies used for the DC to DC converter as listed in detail in [1].

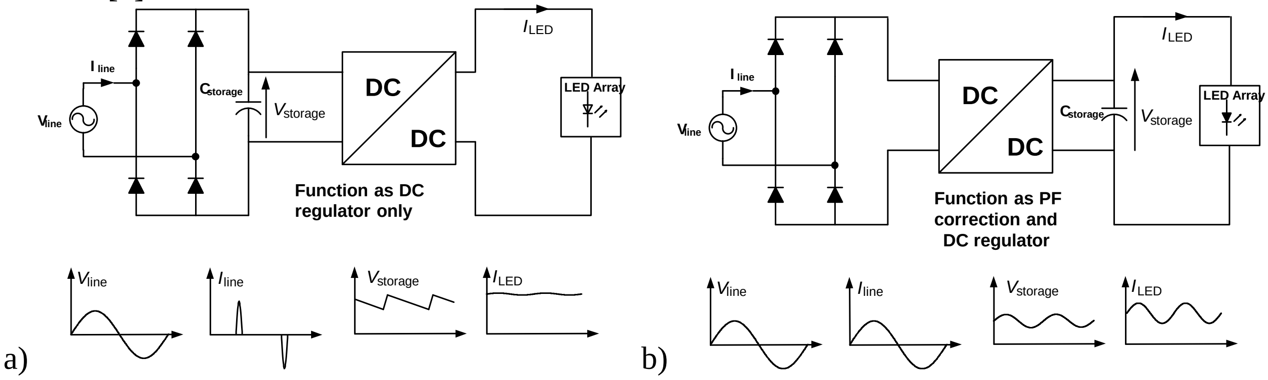

Figure 8: Typical single stage LED driver topologies.

5.2. Two-stage drivers

The contradiction between a sinusoidal input current and a smooth DC output current can be overcome with a two-stage approach. As shown [1], these characteristics are preferred in medium and high power applications, where electrical performance and reliability are more of a concern than cost and size. Depending on the functions of the two stages, particularly of the second stage, S2 drivers can be further classified as Type A and Type B.

The classical approach to a two-stage driver is Type A (see Figure 9). In such S2A drivers, the first stage performs the PF correction and the second stage performs the DC/DC regulation. They are arranged in a cascaded structure with the LED load [2][8][10][23][24][25]. In these drivers, the boost converter is mostly adopted in the PF correction stage for its excellent input current shaping capability and low front-end EMI filter requirements. The second power stage is a high step-down DC/DC converter. The intermediate voltage $V_{storage}$ across the storage capacitor must typically remain larger than the grid voltage in order to ensure a proper function of the PFC. Therefore, the ripple of this voltage must be limited, which requires a large energy storage capacitor, being implemented by an electrolytic capacitor.

Type B (S2B) is a less conventional solution (see Figure 10). Here, the first power stage performs PF correction and DC/DC regulation concurrently, similar to S1B drivers. The second power stage is connected in parallel with the LED load and performs an active filter function [7][26][27]. The active filter is controlled to extract the double-line-frequency power from the DC-link into the energy storage capacitor $C_{storage}$. Consequently, the LED power will be fairly constant and contains little or no low-frequency ripple, thus posing no light flicker issue.

Because of the parallel connection, the second converter doesn't need to process the whole LED power, but only the power needed to cancel the ripple. Therefore, it may be smaller than in topology Type A. However, contrary to Type A, it needs to be a bi-directional converter.

The two converters can be of different topologies. This is discussed in detail in [1].
Contrary to Type A, the ripple of the storage voltage $V_{storage}$ is not limited by any requirements. This means that the energy content of the capacitor can be used to its full extent and the capacitor size can be smaller. In addition, even the voltage range is not limited and can be selected to achieve optimal performance or size.

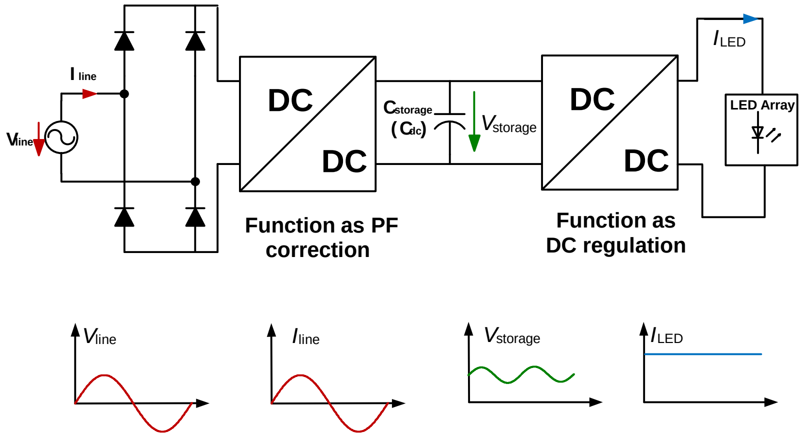

Figure 9: Classical two-stage LED driver topology.

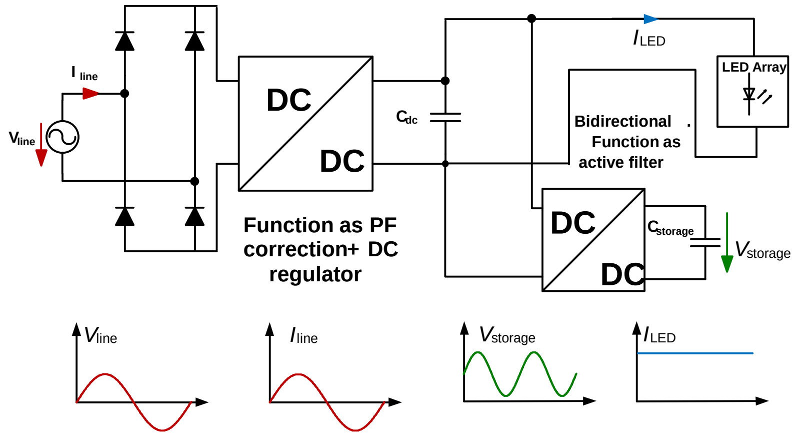

Figure 10: Two-stage LED driver topology with second stage connected in parallel to the LED.

6. Selection of the storage elcap

In most active drivers a capacitor is used to provide a smooth DC output. If the input current is purely sinusoidal, the capacitor must provide the required energy for time, when there is no input power to avoid flickering of the LED. The larger the energy is the larger the volume size of capacitor is. The volume size of capacitors typically scales with the maximum energy E_{max} it may store, which is $E_{max} = ½\, C·U_{max}^2$.
The capacity, rated voltage, diameter and height of 190 electrolytic capacitors are collected from the website of an electronic components distributor [28]. Rated energy and volume are calculated from this data and shown in Figure 11. It is clearly seen that capacitors of different rated voltage and capacity have nearly the same size, if the rated maximum energy is the same. The volume size doesn't scale linearly with the rated energy content, but with an exponent of 0.65 as shown in Figure 11.
In most circuits the whole energy of the capacitor cannot be used, but only the energy difference between the maximum and minimum voltage. It can be shown that the available energy is dependent only on the relative voltage difference, independent of the absolute voltage. If a certain amount of energy is needed, the required capacitor becomes larger, if the voltage difference is only small. Then, only a fraction of the capacitor's storage capability is used. Figure 12 shows for an exemplary amount of energy of 50 Ws, which capacitor size would be necessary as a function of the voltage difference. The orange curve shows the required total energy storage (of which only a

fraction is used) and the blue curve shows the related volume size, derived from the equation in Figure 11. It shows that an increase of voltage variation from 10% to 100% can gain a factor of 3 in volume size of the elcap.
This would relate to the difference of voltage variation between the two-stage topologies Type A and Type B.

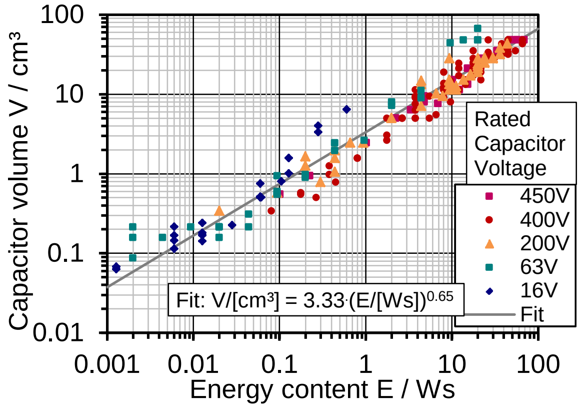

Figure 11: Volume size of elcaps as a function of their rated energy content determined from datasheets.

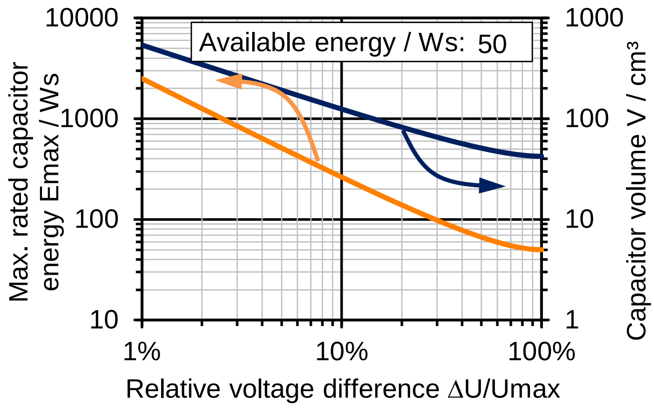

Figure 12: Needed rated energy and volume size of elcaps as a function of the available voltage difference for an exemplary amount of energy of 50 Ws.

7. Conclusions

A survey of existing commercial LED drivers and their related technologies is presented. The data indicate the diversity of LED products in terms of output power and output voltage levels, which is in contrast with existing lighting systems such as incandescent and fluorescent lamps which have standardized discrete rated power levels.
A topology for a highly reliable pure passive LED driver consisting only of inductors, foil capacitors and diodes is shown. Despite its bulky size it is well suited for outdoor street lighting applications. Besides others, it makes use of saturation effects of LEDs.
Different active driver topologies are compared. A two-stage topology, where the second stage is connected in parallel and only used for compensating the output ripple has been discussed as most compact solution with in addition the smallest storage capacitor size.

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