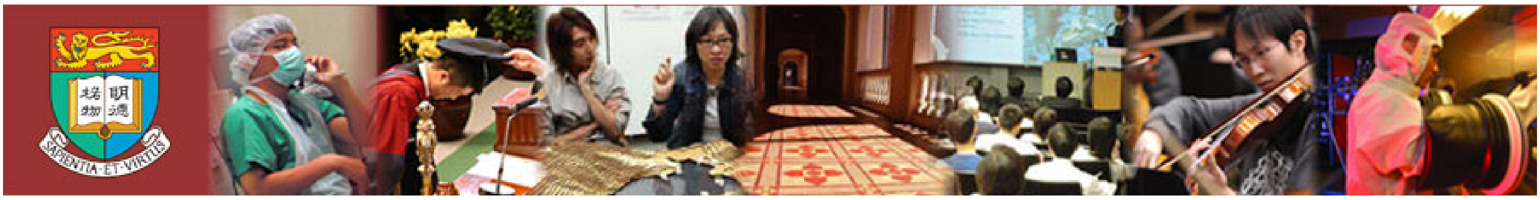

Title	A Survey, Classification and Critical Review of Light-Emitting Diode Drivers
Author(s)	Li, S; Tan, SC; Lee, CK; Tse, CK; Waffenschmidt, E
Citation	IEEE Transactions on Power Electronics, 2015
Issued Date	2015
URL	http://hdl.handle.net/10722/211759
Rights	Creative Commons: Attribution 3.0 Hong Kong License

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2417563, IEEE Transactions on Power Electronics

A Survey, Classification and Critical Review of Light-Emitting Diode Drivers

Sinan Li[1], *Member*, *IEEE*, Siew-Chong Tan[1], *Senior Member*, *IEEE*,
Chi Kwan Lee[1], *Member*, *IEEE*, E. Waffenschmidt[2], *Senior Member*, *IEEE*,
S. Y. R. Hui[1], *Fellow*, *IEEE*, and Chi K. Tse[3], *Fellow*, *IEEE*

[1]Department of Electrical & Electronic Engineering, The University of Hong Kong, Hong Kong
[2]School of Applied Science, Cologne University, Germany
[3]Department of Electronic & Information Engineering, Hong Kong Polytechnic University, Hong Kong

***Abstract*— Based on a survey on over 1400 commercial LED drivers 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 paper also presents an overall view on the technical and cost aspects of the LED technology, which is useful to both researchers and engineers in the lighting industry. Some general guidelines for selecting driver topologies are included to aid design engineers to make appropriate choices.**

I. 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. [1]–[5]. The four major factors supporting the LED's increasing popularity are its (i) long lifetime [6]; (ii) mercury-free structure, [7], [8]; (iii) energy saving property (i.e. high system luminous efficacy exceeding 150 lm/W) [9], [10] and (iv) flexibility of color mixing and control [4], [11]. 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 [1], [2], [6]–[8], [12]–[14], in order to fully utilize their potential benefits. Several distinctive features of LEDs need special attention. Their diode-like *V-I* characteristic implies that a slight variation of the applied voltage across an LED can cause a large fluctuation in its current and subsequently its luminous outputs. Therefore, LED should be powered by a current source instead of a voltage source. Another important feature is the temperature dependent characteristics of their luminous efficacy and color spectra. Luminous efficacy generally decreases with junction temperature [13], which also causes color temperature shift and complicates color control [14].

The complex interactions of the photometric, electric, thermal and chromatic aspects of an LED system have to be understood before any LED system can be optimally designed. The recently developed photo-electro-thermal (PET) theory has provided a platform for studying these 4 aspects of the LED performance. 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* [15], [16]. 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 of about 1462 LED products conducted with the Digikey system [17] in September 2014 and a literature review, this paper aims at providing a classification and an updated overview of LED drivers. The major issues of concern covered in the paper include

- The current status of LED drivers in existing market including the correlations between applications, electrical parameters (output voltage and current ratings), safety measures (e.g. isolations) and cost with respect to power ratings.
- The trend and design challenge (preference) of LED drivers such as international regulations and practical concerns (e.g. factors affecting the lifetime and reliability of LED systems, driving/ dimming methods).
- Classification of LED drivers: Factors affecting the lifetime of LED systems such topologies with or without electrolytic capacitors, current balancing for parallel LED strings, and voltage and current stresses on circuit components are highlighted.
- Guidelines for selecting an appropriate LED driver for a given application.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2417563, IEEE Transactions on Power Electronics

TABLE I TYPICAL POWER DISTRIBUTION FOR VARIOUS LED APPLICATIONS

Power range	1-25 W	25-100 W	>100 W
Power Class	Low	Medium	High
Applications	Ornament/Interior Lighting	Indoor/Outdoor Lighting	Outdoor Lighting, Street Light, Floodlight
Application examples	Light Strip, R-Lamp, Incandescent Replacement, Replacement of CFL Bulb, MR Lamp and PAR Lamp	Down Light, L-Light, Flat Light, PAR Replacement, CFL Replacement, LFL Replacement	HID Floodlight Replacement, HID Street Light Replacement

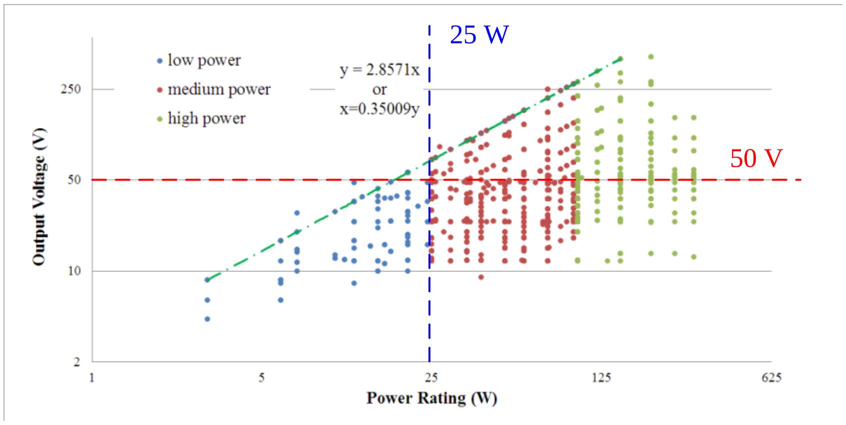

Fig. 1. LED voltage distribution at different power ratings (a result based on 1462 commercial LED drivers).

II. CURRENT STATUS OF LED DRIVERS

Based on the survey on existing commercial LED drivers, the distributions of these products according to their applications, output voltage ratings, galvanic isolation and cost are reviewed. These distributions reflect the existing market needs and imply different specifications for different applications. Such distributions are expected to continue to expand as LED products enter new lighting markets.

A. Power Ratings and Applications

Based on the commercial data collected, 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). Typical applications corresponding to their power ratings are tabulated in Table I. It is noted that the power ratings have certain correlations with the applications. For ornament/interior lighting applications, LED is good replacement for incandescent lamp and compact fluorescent lamps. The power ratings for such retrofit applications are usually low and below 25 W. For general indoor lighting applications (including down light, L-light, flat light and the replacement of several high power traditional lighting sources) where the required luminous output is much higher, the power ratings are typically within the medium power range of 25 W to 50 W. For outdoor applications such as street lighting and floodlight, for which very high luminous output is usually required, the power ratings are from 50 W up to several hundred watts. These applications fall in the medium power or high power class. The broad grouping of the applications in Table 1 will facilitate the discussion on the choice of LED drivers and regulatory requirements in the following sections.

B. Output Voltage and Power Ratings

The ratings of the output DC voltage and current are important factors that affect the selection of the LED driver topologies. These ratings are load dependent. LEDs can be arranged in series or parallel, or a combination of both. Each situation results in its own voltage/current rating. The scenario becomes even more diverse considering the vast variety of LED devices available in the market with different voltage and current ratings. 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 nonlinear scale in Fig. 1. (Note: some data are identical and are overlapped in Fig. 1) Some important observations are listed as follows:

- 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 stark contrast with traditional lighting systems such as incandescent and discharge lamps that have standardized discrete lamp voltage and system power levels.
- As shown in Fig. 1, the data points cover a triangular area on the 2-dimensional plane of the output voltage versus the power rating. Those points lying on the upper boundary line (i.e. the

hypotenuse of the triangle) correspond to LED samples having the maximum rated current value. It is noted that each point has the same rated current of 0.35 A, which happens to be the maximum rated current rating of many commercial LED devices.

- The output voltage of most of the LED products in the low power sector is kept within 50V. According to Low Voltage Directive 2006/95/EC which is mandatory required for the CE Mark scheme [18], 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. For medium and high power products, the range of the output voltage is wider. Some medium and high power products also adopt an output DC voltage below 50 V, taking advantage of the less stringent safety requirements parallel-LED-string configurations. For high power street lighting, a high output voltage with single LED string can reduce circuit complexity.

C. *Galvanic Isolation and Power Ratings*

Fig. 2 illustrates a typical industrial classification of the circuit topologies and their needs for electrical isolation for different power levels by one manufacturer [81]. Only some the products in the survey disclose all technical aspects such as the use of electrical isolation or not. Data of about 150 products with such information are displayed in Fig. 3. The surveyed results clearly indicate that there is no consensus about the requirements of electrical isolation. For example, some manufacturers do not incorporate electrical isolation for their LED products with power less than 25 W as suggested in [81]. For switched-mode (active) LED drivers with power higher than 25 W, electrical isolation is usually preferred. However, existing street lamps based on magnetic (passive) ballasts and discharge lamps do not need electrical isolation. Therefore, passive LED drivers based on similar magnetic ballast structures fall into the same category.

D. *Cost and USD/Watt*

Fig. 4 shows the retail price distribution at different power levels. 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. In order to study the price from a different angle, the US dollar per watt (USD/W) values are plotted in Fig. 5. It is noted that such USD/W decreases with increasing power level. The USD/W changes from 4.6 in the low power sector to 0.5 for the high power sector. This means that for high power applications, the cost per watt is not as critical as in low and medium power applications. The trend in USD/W also provides an explanation for the price saturation in the high power level.

III. DESIGN CHALLENGES OF MODERN LED DRIVERS

This section reviews key criteria in the implementation of LED lighting systems regarding to international regulations and practical concerns. This section focuses on the electrical-related performance of LED systems, with special concerns on reliability.

A. *International Regulations*

Similar to the traditional lighting, an LED system should comply with associated luminaire standards and international regulations. These standards and regulations pose basic requirements over LED systems. They could affect the designer's selection of a proper circuit topology and control method. A survey of these standard and regulations (e.g. *The Energy Star program* and *IEC standard* are most widely adopted for solid-state lighting (SSL) luminaires) with respect to electrical, thermal, safety, warranty aspects are included in Table II.

1) Lifetime and reliability challenges

The lifetime of an LED is usually defined as the lumen maintenance life (in hours), that is, the elapsed operating time over which the LED light source will maintain a percentage *p* of its initial light output, with *p* usually being 50% or 70% [23], [24]. The long lifetime (e.g. 50,000 hours) of modern LED devices is a factor that puts LED technology ahead of other light sources. However, it is necessary to consider reliability of the entire LED system holistically, especially when the LED drivers are integrated

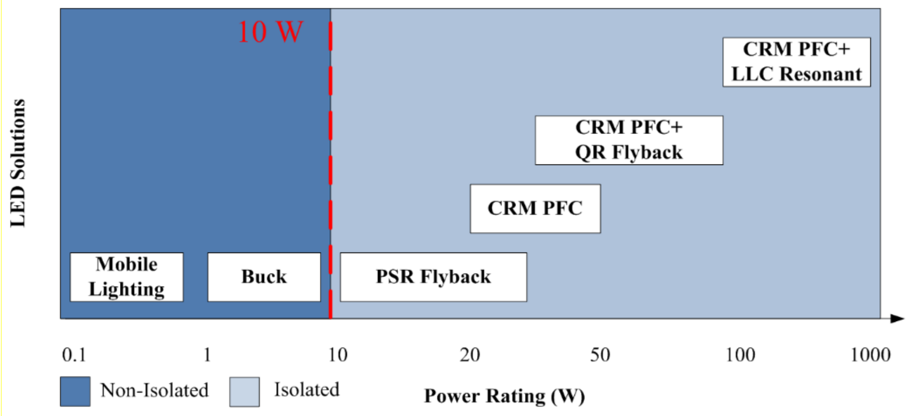

Fig. 2. Circuit topology distribution at different power ratings (Redrawn from [81])

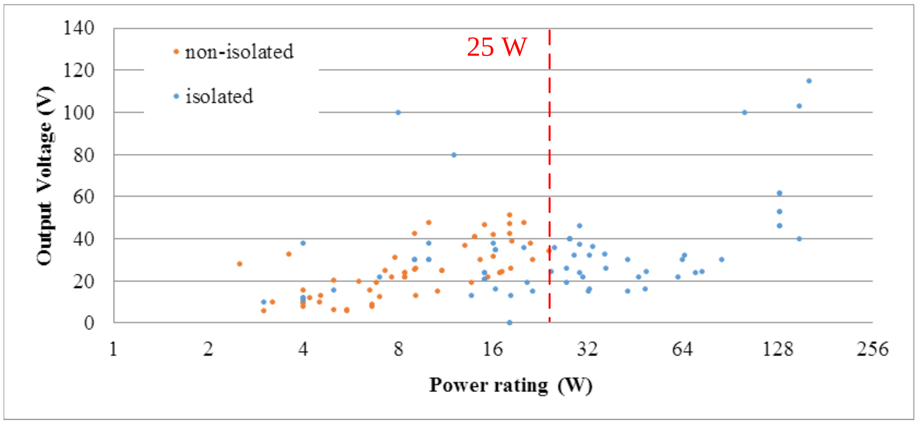

Fig. 3. Power distribution with respect to isolation (a result based on 150 commercial LED drivers).

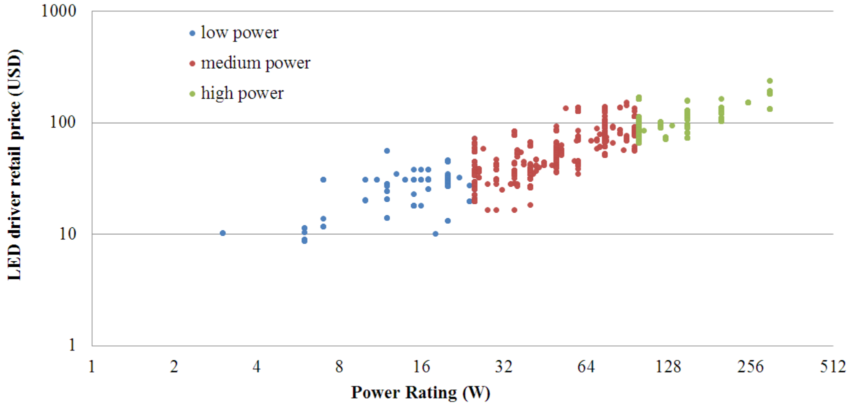

Fig. 4. LED driver retail price distribution (a result based on 1462 commercial LED drivers).

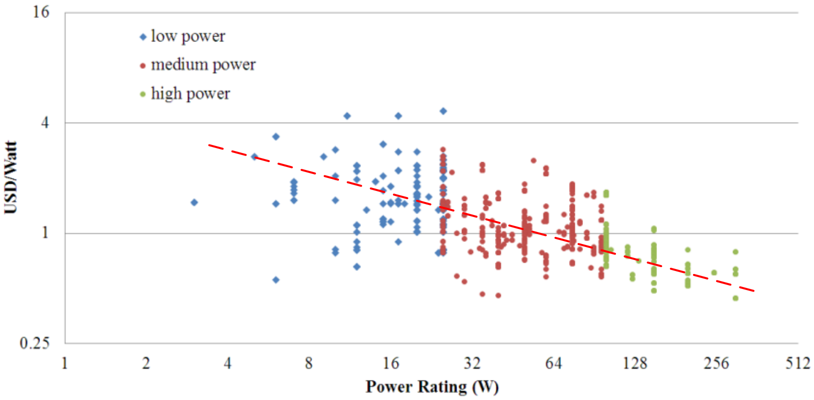

Fig. 5. LED driver USD/W distribution (a result based on 1462 commercial LED drivers). Red dotted line represents an approximation of the USD/W trend.

into the products and not designed to be replaceable. The minimum lifetimes of residential and commercial products are stipulated in the Energy Star program as shown in Table II.

For the LED devices, a critical factor for their lifetime is heat. The light output of LED decays exponentially with an increase in junction temperature [5], [23], [13] and shortens the lifetime of the LED [5], [20]–[23]. For the LED drivers, the lifetime is limited by the shortest lifetime of the circuit components. Electrolytic capacitor (E-Cap), commonly used in many switched-mode LED drivers, has been identified as a weak link because of its relatively short lifetime [25]. There has been increasing research on eliminating the use of E-cap in lighting products. Besides component failure, other reliability issues include current sharing of parallel LED strings [69], open and short circuit fault protection, and the

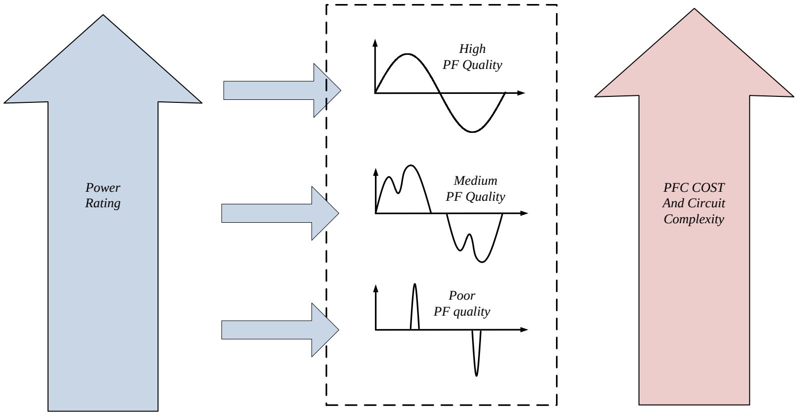

Fig. 6. Relationship between power level, associated PF requirement and expected system cost and complexity on power factor correction (PFC).

TABLE II SOME LED DRIVER SPECIFIC STANDARD AND AGENCY REQUIREMENTS

Item	Reference	Criteria
Power Factor (PF)	Energy Star Program Requirements for Solid-State Lighting Luminaires Version 1.1 (Effective date: Feb 1, 2009)	Residential ≥ 0.7 Commercial ≥ 0.9
	Energy Star Program Requirements Product Specifications for Luminaires (Light Fixtures) Version 1.0 (Effective date: Oct 1, 2011)	≥0.5 for ≤5 W Residential ≥ 0.7 for > 5 W Commercial ≥ 0.9 for > 5 W
Total Harmonic Distortion (THD)	EN(IEC) 61000-3-2 Class C (Lighting)	Class C for > 25 W Class D for ≤ 25 W
Operating Temperature	NEMA SSL 1-2010	−40~60 °C
Electromagnetic and Radio Frequency Interference	Energy Star Program Requirements Product Specifications for Luminaires (Light Fixtures) Version 1.0 (Effective date: Oct 1, 2011)	Residential: Class B in FCC requirement Commercial: Class A in FCC requirement
Minimum Efficacy	Energy Star Program Requirements Product Specifications for Luminaires (Light Fixtures) Version 1.0 (Effective date: Oct 1, 2011)	Non-directional residential: ≥70 lm/W Directional residential: 29~70 lm/W Directional commercial: 29~42 lm/W
Warranty	Energy Star Program Requirements Product Specifications for Luminaires (Light Fixtures) Version 1.0 (Effective date: Oct 1, 2011)	Non-replaceable Drivers: 5 years Replaceable drivers: 3 years
Operation Frequency	Energy Star Program Requirements for Solid-State Lighting Luminaires Version 1.1 (Effective date: Feb 1, 2009)	≥ 120 Hz
	Energy Star Program Requirements Product Specifications for Luminaires (Light Fixtures) Version 1.0 (Effective date: Oct 1, 2011)	≥ 120 Hz (Dimming at all light outputs)
Dimming	Energy Star Program Requirements Product Specifications for Luminaires (Light Fixtures) Version 1.0 (Effective date: Oct 1, 2011)	Continuous dimming from 35% to 100% of total light output
Safety	CE mark, EN61347-2-13; UL 8750,1012; CSA C22.2 No.107.1 -01; IEC 61347-2-13, etc.	-
Transient Protection	Energy Star Program Requirements Product Specifications for Luminaires (Light Fixtures) Version 1.0 (Effective date: Oct 1, 2011)	ANSI/IEEE C62.41.1-2002 and ANSI/IEEE C62.41.2-2002, Class A
CCT	IES LM-79-08	-
CRI	Energy Star Program Requirements for Solid-State Lighting Luminaries Version 1.1 (Effective date: Feb 1, 2009)	Indoor luminaires: ≥75

ability to withstand wide temperature variation, voltage sag or swell, and voltage transients arising from lightning strikes [26].

2) Flickering

Flicker is defined in [78], [79] as a rapid and repeated change of brightness over time. Visible flickers (lower than 60-90 Hz) and invisible flickers (up to 200 Hz) could cause retinal neurological effects [79]. In the *Energy Star* program, a minimum operating frequency of 120 Hz is required to avoid noticeable flickering (see Table II).

Besides health concerns, flicker should be avoided in applications where super-slow-motion images is required, or where rotating machinery is in use under certain circumstances [80]. The tolerance of flicker at a minimum frequency of 120 Hz has implications of the LED driver design. For offline LED products, the size of the buffer capacitor influences the LED current ripple. For applications where little flicker is allowed, either a large capacitor or active filtering techniques [1], [4], [58], [62] can be used.

B. *Other Issues*

1) *Form factor*

For high-power outdoor 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. The form factor in many retrofit applications (such as replacements of incandescent light bulbs and CFLs) imposes severe constraints on the LED driver designs. New development of LED bulbs without heat sink has recently been reported in [82]. If the price can be brought down with such technology, these new LED bulbs can become the dominant products in the retrofit market.

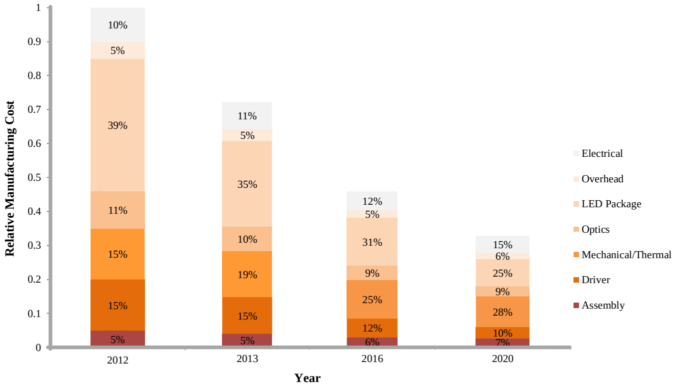

Fig. 7. Suggested cost reduction targets for a Typical A19 Replacement Lamp (redrawn from [19]).

2) *Down-sprialing costs*

The U.S. Department of Energy (DOE) SSL program has published the projected LED luminaire cost as shown in Fig. 7, of which the driver constitutes 10% to 15% of the total manufacturing cost [19]. It is projected that the cost of LED systems be reduced by 70% every four years. The significant drop in costs will no doubt put more pressure on the system designs. The new LED bulb without heat sinks is a good response to such challenge.

From the survey data obtained, the LED products are broadly classified into 6 groups as shown in Table III. They are divided into two categories depending on whether the rated power exceeds 25W or not. The regulatory and empirical requirements are summarized in the table. Such information will be linked to Table VII and the flow chart (Fig.16) for making an appropriate choice of circuit topology.

IV. Driver Classification And Selection

In this section, circuit topologies suitable for LED drivers are described and classified. The topologies are first categorized into passive LED drivers and switched-mode LED drivers based on whether high-frequency switching operation is performed. Passive (*P*) drivers do not perform high-frequency switching operation and are thus simpler and more reliable. Without tight output current control, they usually provide a DC current with AC current ripple. They are reliable for outdoor applications and are cost effective for some retrofit low-power applications. Switched-mode (*S*) drivers operate at high frequency and can realize compact size, low power loss, and precise output regulation. These properties allow them to have a broader range of applications. They are usually less reliable than passive drivers and are vulnerable to extreme weather conditions such as wide temperature variation and lightning. Both the passive and switched-mode LED drivers are further sub-classified into various types, according to their topological configurations, and their respective pros and cons are studied and compared.

A. *Passive LED Drivers*

Passive drivers do not contain active switches, gate drives, integrated circuits, controllers or auxiliary power supplies. They comprise only passive components (e.g. resistor, capacitor, magnetic components (e.g. inductor/ transformer) and diodes, and are operated at line or double-line frequency. Without any means of active control, a passive driver must adopt some current limiting impedance between the AC line and the designated LED load. Such impedance can be lossy or (ideally) lossless. Therefore, the passive topologies can be further sub-classified into two types, namely Passive Type I (*P1*) which are lossy, and Passive Type II (*P2*) which are (ideally) lossless.

P1 driver is of the lossy type. The current limiting impedance can be either a resistor or a linear regulator (linear regulators are not passive devices, but are included here to reflect their lossy properties). Fig. 8 illustrates a *P1* driver using a current limiting resistor R_{limit} with a front-end low frequency transformer before the diode rectifier [27].

Direct conversion from a high line voltage (220 V_{RMS}) to the LED load without a step-down transformer would result in an unacceptably low system's efficiency. The very low efficiency is due to conduction loss of R_{limit}. Alternatively, the use of a step-down transformer can reduce the voltage across R_{limit}. However, the conduction loss in R_{limit} is still significant. Moreover, the transformer also introduces core losses.

Another drawback of *P1* drivers is that the filter capacitor C_{storage} must be large enough to provide smooth DC power to the LED load in order to avoid flickering. Typically, such a capacitor is of the electrolytic type. Their pulsating input currents consist of substantial harmonics.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2417563, IEEE Transactions on Power Electronics

TABEL III DESIGN CHALLENGES FOR DIFFERENT POWER CLASSES.

		High power (>100 W) Medium power (100 W~25 W)			**Low power (< 25 W)**		
	Requirement / Criteria	*Group A*	*Group B*	*Group C*	*Group D*	*Group E*	*Group F*
Regulatory requirement	Power Factor (PF)	Residential ≥ 0.7 Commercial ≥ 0.9			≥0.5 for≤5 W: Residential ≥ 0.7 for > 5 W Commercial ≥ 0.9 for > 5 W		
	Total Harmonic Distortion (THD)	Class C			Class D		
	Electromagnetic and Radio Frequency Interference	FCC 47 CFR part 15					
	Minimum Warranty	Non-replaceable Drivers: 5 years Replaceable drivers: 3 years					
	Other Criteria	Refer to Table II					
Empirical requirement	Efficiency	Very high (e.g. >90%)	High (e.g. >85%)		Medium (e.g. >70%)		Normal (e.g. >50%)
	Cost (USD/Watt)	For most high power outdoor applications: Less critical For indoor applications: Critical					
	Perform PFC?	Yes					No
	Size (form factor)	For most high power outdoor applications: Less critical For indoor applications: Critical For retrofit applications: Very critical					
	E-Cap preferred?	Yes	No	Yes	No	Yes	
	Suggested safety level (regarding to isolation, OC/SC/Over current protections ability)	Very high	High		Medium		Normal
	Ability to stand against lightning	critical for outdoor applications			Less critical		

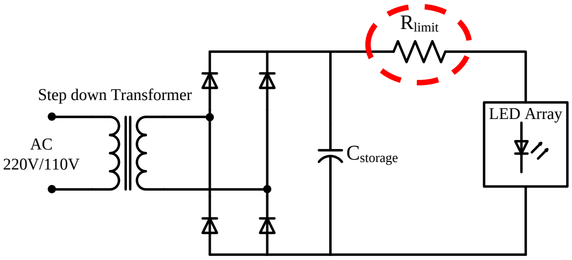

Fig. 8. Passive Type I (P1) LED driver.

The PF of such circuits is low and marginally satisfies the Class D limit [27].

P2 drivers use ideally lossless impedance (an inductor, capacitor or their combinations) to limit the LED output current. The impedance must be placed on the AC side to perform the current limiting function. One such example is given in Fig. 9 [26], where an inductor L_s is used to withstand the voltage difference between the input voltage V_s and output voltage V_o, thereby eliminating the need for a less efficient, low-frequency transformer. Moreover, L_s can act as an input filter to smoothen the input current I_s such that only a small non-electrolytic capacitor is required on the DC side. This eliminates the need to use E-cap in the driver, while still achieving a good PF and EMI performance at the input. Note that the valley-fill circuit in Fig. 9 can be replaced by a non-E-cap as shown in Fig. 10 [30].

Another example of *P2* drivers is illustrated in Fig. 11 [10]. This is a retrofit driver to replace existing fluorescent lamp ballast. The current limiting inductors are placed in the auxiliary circuit immediately at the AC output of the existing fluorescent ballast. Generally, retrofit designs for interchangeable fluorescent and LED ballasts are not optimal solutions. Energy efficiency is compromised due to the cascaded structure.

Table IV gives a comparison of the three passive LED drivers. It is evident that some *P2* drivers are more energy efficient than *P1* drivers. The efficiencies of the circuits shown in Fig. 9 and Fig.10 are even better than that of switched-mode drivers. Also, both *P2* drivers satisfy the low input current THD limit. With proper photo-electro-thermal designs, LED systems with *P2* drivers have been commercialized for street lamp applications without noticeable flickering problems [28].

In order to evaluate the capacitance requirement used in each topology for different power levels, (i) capacitance per watt and (ii) maximum capacitive energy storage per watt are introduced in Table IV. These parameters are good indicators for the choices of capacitors. If they are large, E-caps have to be used since they have the highest capacitance density. Otherwise, non-E-caps can be used. The topology

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2417563, IEEE Transactions on Power Electronics

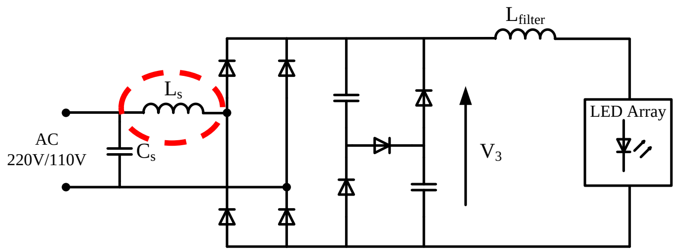

Fig. 9. Passive Type II (P2) LED driver example 1.

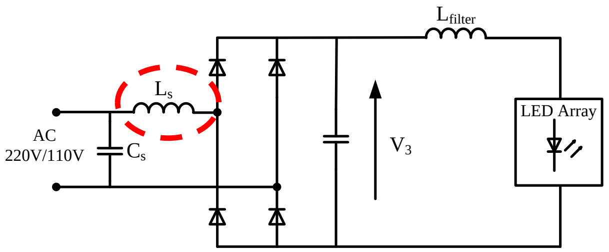

Fig. 10. Passive Type (P2) LED driver example 2.

in Fig. 11 has the lowest overall capacitance per watt (0.33 μF/W) and maximum energy storage per watt (0.007J/W) among the four passive drivers in Table IV.

Despite their bulky size and heavy weight of the large inductor required in the circuit, passive LED drivers offer superior reliability since they comprise no active switch, gate drives, integrated circuits and controllers, external power supplies, and E-caps. These properties are highly desirable for outdoor applications where system reliability is of prime concern and space constraint is less critical. In fact, the patented passive driver in Fig. 10 has reached the production stage for street lighting applications in South China where lightning exceeding 10,000 times per day in the summer is not uncommon and in North China where extreme low temperature persists in the winter. Despite the lack of tight output current regulation (control), their power sensitivity with input voltage fluctuation can be reduced by proper passive driver design [30]. They are also compatible with external central dimming system, such as tap-changing transformers.

B. Switched-Mode LED Drivers

Switched-mode LED (*S*-type) drivers take advantage of high-frequency operation and active control so that good driver compactness and tight output current regulation can be achieved. Functions such as PFC, current sharing, dimming, isolation, circuit fault protection and thermal tracking can be easily incorporated into *S*-type drivers to meet different applications' needs. These superior properties make S-type drivers very attractive for a wide range of indoor applications. Recently, a vast variety of switched-mode LED driver topologies have 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. As the number of power stage increases, circuit complexity and the associated cost increases simultaneously.

1) Single-Stage Drivers

Switched-mode single-stage (*S1*) drivers have only one power conversion stage and usually have low component count. However, it is often difficult for *S1* drivers to ensure good performance in many aspects (such as high efficiency, good PF, and constant current output) simultaneously. According to Table III, *S1* drivers are suitable for low and some medium power class applications (<50W) where size and cost are usually more critical than PFC and efficiency. High power applications, on the other hand, have more stringent regulations which usually disqualify the use of *S1* drivers. Depending on the location of the storage capacitor $C_{storage}$, *S1* driver can be further sub-classified into *Type A* and *Type B* (Fig. 12 and 13).

Fig. 12 illustrates a schematic of the *switched-mode single-stage Type A* (*S1A*) driver, which has its storage capacitor C_{storage} directly connected on the low frequency side. One merit of a *S1A* driver is that its output can be designed to exhibit small voltage and/or current ripple if the

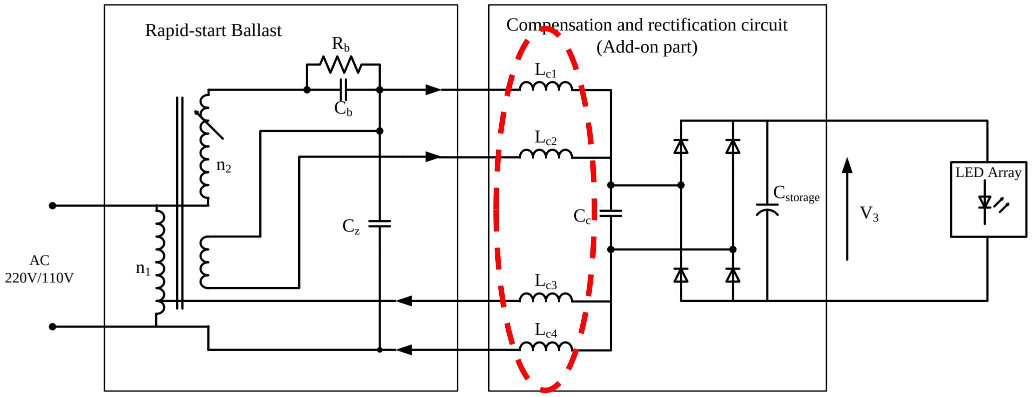

Fig. 11. Passive Type (P2) LED driver example 3.

TABLE IV COMPARISON BETWEEN VARIOUS TYPES OF PASSIVE (P1, P2) LED DRIVERS.

Driver Type	**Power Rating (W)**	**Efficiency**	**Total Capacitance (μF)**	**Inductance (H)**	**THD satisfy**	**Volume & weight**	**Output current**	**Cap/ Power (μF/W)**	**Max Cap Energy Storage /watt (J/W)**
P1 **(Fig. 8)** [27]	10.4	50%	4700	Transformer $L_{\text{Magnetizing}}$=2.97	Class D	large	DC	452 μF/W	0.0298
P2 **(Fig. 9)** [26]	47	93.6%	40.3	L_S = 1.47 L_{filter} = 1.9	Class C	large	DC	0.9 μF/W	0.011
P2 **(Fig.10)** [29]	150	94%	50	Ls=0.3 L_{filter}=0.8	Class C	large	DC	0.33 μF/W	0.007
P2 **(Fig. 11)** [10]	20	72.9%	50.3	4 × 0.5	Class C	large	DC	2.5 μF/W	0.0245

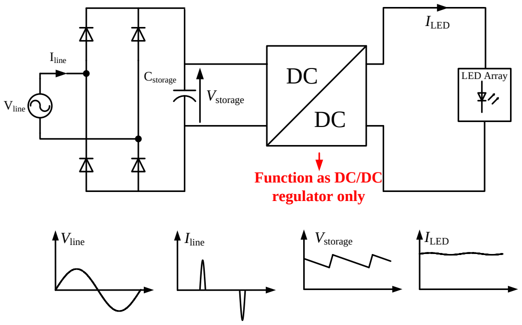

Fig. 12. Switched-mode single-stage Type A (S1A) driver.

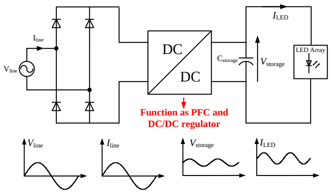

Fig. 13. Switched-mode single-stage Type B (S1B) driver.

low-frequency storage capacitor is adequate to handle the pulsating power between the input and output stages. Similar to the case of *P1* drivers, however, the adoption of a bulky low-frequency capacitor and its pulsating input current (shown in Fig. 12 as I_{line}) are the main drawbacks of *S1A* drivers. *S1A* drivers are only applicable to very low power applications, typically below 5 W [31], [32].

In *switched-mode single-stage Type B* (*S1B*) drivers, the capacitor is placed on the high-frequency side after the DC/DC converter, as illustrated in Fig. 13. Here, the single DC/DC converter provides both PFC 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 capacitance $C_{storage}$ 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, and their required capacitance is similar to that of *S1A*. In general, a Capacitance/W value of 1 μF/W is a very common value for DC-link capacitors in such PFC converters [33], [34].

Some *S1B* topologies ($\text{S1B}_{\text{hybrid-PFC}}$) share one active switch [35]–[37] in the two-stage power processing for achieving PFC and DC/DC functions. It is difficult to achieve both functions simultaneously at the same optimal state to give the highest possible power conversion efficiency. For topologies that are designed to work in critical conduction mode (CRM) or discontinuous conduction mode (DCM) that are known to achieve PFC inherently ($\text{S1B}_{\text{inherent-PFC}}$), this will be less of a problem.

An important issue associated with all *S1B* drivers is their low energy efficiency, especially when the output voltage is relatively low. This is due to the short duty cycle operation, and a longer time interval is required for the energy to circulate rather than to go directly to the load. Circulating energy causes power loss along the energy circulating path.

Classical topologies including the buck [12], [36], [38], [39], buck-boost, SEPIC [40], [41], flyback [42], [43], half-bridge [44], push-pull converters [45] can all be used as *S1B* drivers. PFC can also be performed passively with valley-fill circuits [46]. Recently, many of these topologies have been modified to achieve high efficiency operation. For most non-isolated topologies, if the duty cycle can be enlarged while achieving the same step-down conversion ratio, energy efficiency can be improved. These topologies are usually referred to as high conversion ratio converters.

Cascaded step-down topologies, such as quadratic buck and cubic buck converters can achieve a high step-down conversion ratio. However, they are not preferred due to the high component count and the requirement of multi-stage power processing (leading to low efficiency), even though they use only one active switch [47]. Other approaches, namely coupled-inductor modified converters [37], [38], [48]–[55], and valley-fill modified converters [27], [43], [49], offer a simple solution to the step-down ratio requirement without over-compromising the efficiency and system complexity. It is possible to further improve energy efficiency by re-circulating the leakage inductor energy of the coupled-inductor back into the circuit, using active or passive clamping techniques [50], [52]–[55]. Note that both the valley-fill circuit and coupled-inductor cell can be concurrently applied to the same converter to achieve an even higher conversion ratio [49].

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2417563, IEEE Transactions on Power Electronics

TABLE V COMPARISON BETWEEN VARIOUS KINDS OF SINGLE-STAGE TYPE B (S1B) LED DRIVERS.

Isolation Type	**Structures**	**High Step Down Ability?**	**High Efficiency?**	**Structures**	**High Step Down Ability?**	**High Efficiency?**
Non-Isolated S1B	Buck-Boost [57]	×	×	Coupled-Inductor Buck [58]	√	√
	SEPIC [59]	×	×	Coupled-Inductor SEPIC [48]	√	√
	Resonant-Assist Buck [7]	×	×	Valley-Fill Modified SEPIC [41]	√	√
	Quasi-Active PFC with Buck [46]	×	×	Quadratic and Cubic Buck [60]	√	×
				Quadratic Buck-Boost [61]	√	×
Isolated S1B	Flyback [42]	√	×	Hybrid Buck with Flyback [62]	√	×
	Hybrid Buck-Boost with Flyback [35]	√	×	Hybrid Boost with Forward [63]	√	×
	Hybrid Boost with Flyback [37]	√	×			

Attaining a high conversion ratio with galvanic (transformer) isolation is straightforward. Traditionally, energy in the leakage inductance of the transformer is lost due to hard switching. Such power loss is the main power loss in such circuits. Of all isolated topologies, the flyback converter is most widely used for AC/DC rectification because of its simple structure and high PF. Its efficiency can be improved by re-circulating the leakage energy [35] or using soft-switching techniques [56]. Table V summarizes some *S1* type of drivers reported in the literature.

2) *Two-Stage Drivers*

Two-stage (*S2*) drivers, which comprise two power processing stages, can offer better performance than its single-stage (*S1*) counterparts in terms of PFC and the reduction of low-frequency output current ripple with the minimum capacitance per watt value. As shown in Table III, 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.

For Type A (*S2A*) drivers (Fig. 14), the first stage performs the PFC and the second stage performs the DC/DC regulation. They are arranged in a cascaded structure with the LED load [1], [7], [12], [35], [64], [65]. The boost converter is mostly adopted in the PFC 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. A major problem with *S2A* drivers is the requirement for a large energy storage capacitor $C_{storage}$, which is usually of the electrolytic type.

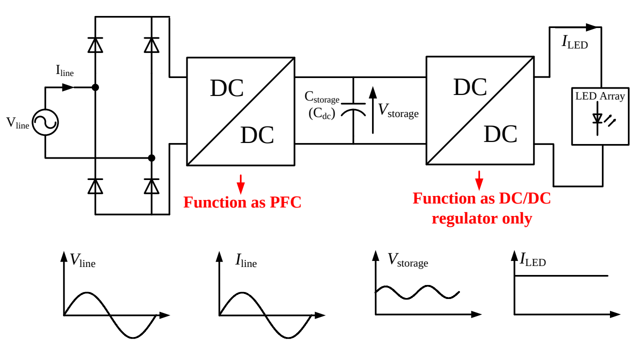

Fig. 14. Switched-mode two-stage Type A (S2A) driver.

For Type B (*S2B*) drivers (Fig. 15), the first power stage performs PFC and DC/DC regulation concurrently. The second power stage performs an active filter function [6], [66], [67], and is connected in parallel with the LED load. 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. Moreover, by decoupling the double-line frequency power from the DC-link and allowing voltage variations on $C_{storage}$, a non-E- Cap with reduced capacitance can be used to process the pulsating power of the input source.

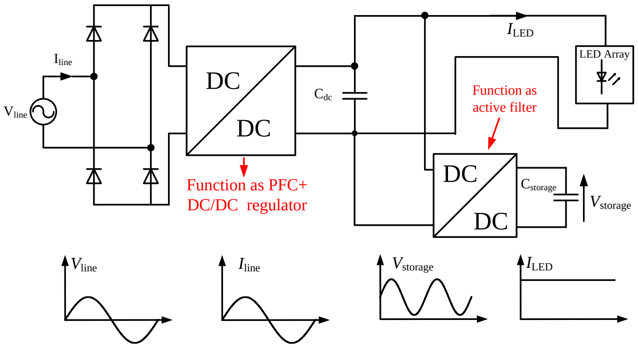

Fig. 15. Switched-mode two-stage Type B (S2B) driver.

TABLE VI COMPARISON BETWEEN VARIOUS KINDS OF TWO-STAGE (S2A, S2B) LED DRIVERS.

Type	**Stage Component**	**Power Rating(W)**	**Max. Cap. Energy Storage per Watt (J/W)**	**Cap/Power (μF/W)**
S2A	Boost (PFC) + Flyback (DC/DC) [1]	60 (output pulsating)	**0.00568**	2.5 (flickering)
	buck (PFC) + half-bridge [12]	18	**0.01**	1.44 (with large inductor)
	Non-cascading boost (PFC) + buck (DC/DC) [7]	100 (high voltage on cap)	**0.156**	91 (conventional)
S2B	Flyback (PFC+DC/DC) + Bidirectional buck/boost converter (active filter) [66]	33.6	**0.00446**	**0.53 (flicker free)**
	Modified Flyback [6]	13.5	**0.0067**	**0.96 (flicker free)**
	H-bridge rectifier (PFC+DC/DC)+H-bridge (active filter) [67]	100	**0.002646**	**0.0147 (flicker free)**

A few possible circuit configurations exist for S2B drivers. In [66], the first stage is a flyback converter which performs the PFC and DC/DC regulation, and the second stage is a bidirectional buck-boost converter which performs active filtering. In [67], the active filter is of inverter type which allows an even larger voltage variation on C_{storage}, resulting in the use of minimal capacitance. Specifically, the capacitance per watt of C_{storage} is only 0.0147 μF/W for the configuration reported in [67], compared to 0.52 μF/W for the configuration reported in [66], given a 600 V amplitude capacitor voltage variation.

Table VI lists the capacitance per watt values for various *S2* drivers. Compared with the values for *S1* drivers shown in Table IV, the capacitance per watt values for *S2B* drivers are at least one order of magnitude lower than those required in other configurations (e.g., *P1*, *S1* and *S2A* types). *S2B* drivers can therefore be realized without E-caps. The expected lifetime of the driver in [67] is that that of LEDs. This idea of active filtering is applicable to any *S1B* driver, turning it into a *S2B* driver.

It is important to note from Table VI that there are some *S2A* drivers which can achieve a low value of capacitance per watt as *S2B* drivers do. This is possible because some degree of ac ripple is allowed in the LED current or on the DC bus voltage. For the former case, In order to avoid flickering caused by such AC current, it is necessary to limit the ratio of the AC current and the DC current. The use of larger inductors for energy storage can also reduce the value of capacitance per watt. As the second stages of the *S2B* drivers do not handle the full LED power, *S2B* drivers could in principle be more energy efficient than *S2A* ones. However, such gain in efficiency can only be achieved with proper low-loss design of the front-stages of the *S2B* drivers, which have to provide both of the PFC and output regulation functions.

3) Three-Stage Drivers

Three-stage (*S3*) drivers are targeted at multi-string LED loads for high power applications. The first two stages of an *S3* driver are made up of regular *S2* drivers, and the third stage is a current post-regulator that provides current sharing among individual LED strings. Dimming control can be realized via a post-current regulator. Naturally, the cost and component count of the post-regulator increase as the number of strings increases.

There are several types of post-regulators, namely the linear type, the DC/DC converter type, and the switch type. The first two types provide DC output current regulation, which can be used for achieving current sharing and dimming (amplitude dimming), while the switch type produces pulsating current and is typically used for dimming applications (PWM or *n*-level PWM dimming).

When used for current balancing, the use of traditional linear post-regulators such as BJT transistors or MOSFETs incurs severe power losses. This is because the regulators have to withstand the full voltage difference between the driver and the LED load. The power loss issue can be alleviated by using a series of current mirrors, where only the voltage differences between strings are compensated [68]–[70]. Nevertheless, the linear type post-regulators are of low cost and have simple circuit implementation, thus guaranteeing higher reliability than the DC/DC converter based post-regulators. For outdoor applications where reliability is of prime concern, DC/DC type post-regulators are unsuitable. The coupled inductors and the daisy-chained coupled inductors suggested in 1992 [71] are good passive options for reducing current imbalance in parallel LED strings. This idea was later repeated in [72]–[75].

To reduce system costs, one solution is to adopt the single-input-multiple-output topology in the second-stage converter, thereby eliminating the need for an additional post-regulator circuit in the third stage [76]. Current sharing is easily achieved through a common control signal. In [77], the mag-amp, which is a highly efficient and reliable device that has a simpler structure compared to the multiple-output converter topologies, is incorporated as the post-regulator to achieve current sharing.

The switch-type post-regulators are mainly for dimming applications. The grouping described in Table III is linked to the passive driver classification (Table IV) and active

TABLE VII COMPARISON OF VARIOUS CURRENT POST-REGULATORS USED IN THREE-STAGE (S3) LED DRIVERS.

Post-Regulator Type	**Component of Post-Regulator**	**LED Current**	**Structure**	**Cost**	**Reliability**	**Efficiency**	**Dimming**	**Current Sharing**	**Open/Short Circuit Protection**
Linear Type	BJT transistor	DC	Simple	Low	High	Low	Amplitude Mode	External circuit	External circuit
	MOSFET								
	Current mirror based circuit								
Switch Type	BJT transistor	PWM pulsating	Simple	Low	Low	High	PWM, *n*-level, or phase-shift PWM Mode	External circuit	External circuit
	MOSFET								
DC/DC Converter Type	Twin-bus buck	DC	Complicated	High	Low	High	Amplitude Mode	External circuit	External circuit
	Multiple transformer (after a common *LLC* or buck-boost converter)		Complicated	High	High	High	Amplitude Mode	Inherent	Inherent
	Coupled inductor (after a common cap isolated converter)		Complicated	High	High	High	Amplitude Mode	Inherent	Inherent
	Mag-amp assisted rectifier (after a common forward converter)		Simple	High	High	High	Amplitude Mode	Inherent	Inherent

TABLE VIII CIRCUIT TOPOLOGIES SELECTION VS. DIFFERENT REQUIREMENT.

Requirement / **Items**	*Group A*	*Group B*	*Group C*	*Group D*	*Group E*	*Group F*
P1	×	×	×			Retrofit solution with low cost
P2	×	Simple structure, high reliability, efficiency and recyclability	×		×	Retrofit solution with low cost
S1A	×	×	×	Simple structure and controllers, low cost	×	Simple structure and controllers, low cost
S1B	×	Simple structure, compact size, low cost, good PF and low THD but might contain flicker using non-E-Cap	Simple structure, compact size, low cost, good PF and low THD	Simple structure, compact size, low cost, good PF and low THD	Simple structure, compact size, low cost, good PF and low THD	×
S2A	High efficiency, good PF and low THD	good PF and low THD but might contain flicker, and with compromised efficiency, using non-E-Cap	High efficiency, good PF and low THD		×	×
S2B	×	E-Cap free, good PF and low THD	×		×	×
S3	Dimming, current sharing, open/ short circuit/over temperature protection	×	×		×	×

driver classification (Table V －VII). Their relationships are tabulated in Table VIII.

C. Guidelines for Topology Selection

With the information provided in Tables II-VIII, some general guidelines are suggested for selecting the appropriate driver topology for a given application as shown in the flow chart of Fig.16. While there are always exceptions and special cases, such flow chart allows one to consider some appropriate topologies particularly if the choice of electrolytic capacitor is an issue.

V. CONCLUSIONS

This paper presents an updated survey of existing commercial LED drivers and their related technologies with considerations of their compliance to regulations, technological challenges, and application requirements. The data indicate the diversity of LED products in terms of output power and output voltage levels. Such a situation is in stark contrast with existing lighting systems such as incandescent and fluorescent lamps which have standardized discrete rated power levels. The surveyed data highlight the need for international standards.

The LED drivers have been systematically classified into passive (P) types and switched-mode (S) types, and then sub-classified respectively into types P1, P2 and types S1, S2, S3 according to their topological configurations. The advantages and disadvantages of these topologies are reviewed. An important parameter, namely capacitance per watt, has been adopted for comparing various driver topologies as such information allows engineers to determine which topologies can avoid the use of electrolytic capacitors. Based on the applications and the technical information provided in this study, some general guidelines are suggested as a general tool for selecting driver topologies.

ACKNOWLEDGEMENT

The authors are grateful to the Hong Kong Research Grant Council for its financial support for the Theme-based Research Project T22-715/12N.

REFERENCES

[1] L. Gu, X. Ruan, M. Xu, and K. Yao, “Means of eliminating electrolytic capacitor in AC/DC power supplies for LED lightings,” *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1399–1408, May 2009.

[2] X. Ruan, B. Wang, K. Yao, and S. Wang, “Optimum injected current harmonics to minimize peak-to-average ratio of LED current for electrolytic capacitor-less AC-DC drivers,” *IEEE Trans. Power Electron.*, vol. 26, no. 7, pp. 1820–1825, Jul. 2011.

[3] M. Arias, D. G. Lamar, J. Sebastian, D. Balocco, and A. A. Diallo, “High-efficiency LED driver without electrolytic capacitor for street lighting,” *IEEE Trans. Ind. Appl.*, vol. 49, no. 1, pp. 127–137, Jan. 2013.

[4] “Philips HUE.” [Online]. Available: http://www.meethue.com/en-US.

[5] N. Narendran and Y. Gu, “Life of LED-based white light sources,” *J. Disp. Technol.*, vol. 1, no. 1, pp. 167–171, Sep. 2005.

[6] W. Chen and S. Y. R. Hui, “Elimination of an electrolytic capacitor in AC/DC light-emitting diode (LED) driver with high input power factor and constant output current,” *IEEE Trans. Power Electron.*, vol. 27, no. 3, pp. 1598–1607, Mar. 2012.

[7] X. Qu, S. C. Wong, and C. K. Tse, “Noncascading structure for electronic ballast design for multiple LED lamps with independent brightness control,” *IEEE Trans. Power Electron.*, vol. 25, no. 2, pp. 331–340, Feb. 2010.

[8] W. K. Lun, K. H. Loo, S. C. Tan, Y. M. Lai, and C. K. Tse, “Bilevel Current Driving Technique for LEDs,” *IEEE Trans. Power Electron.*, vol. 24, no. 12, pp. 2920–2932, Dec. 2009.

[9] M. Arias, A. Vazquez, and J. Sebastián, “An overview of the AC-DC and DC-DC converters for LED lighting applications,” *Autom. J. Control Meas. Electron. Comput. Commun.*, vol. 53, no. 2, pp. 156–172, May 2012.

[10] H. Kim, B. Lee, and C.-T. Rim, “Passive LED driver compatible with rapid-start ballast,” in *Proc. 8th Int. Conf. on Power Electronics - ECCE Asia*, 2011, pp. 507–514.

[11] Y.-K. Lo, K.-H. Wu, K.-J. Pai, and H.-J. Chiu, “Design and implementation of RGC LED drivers for LCD backlight modules,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4862–4871, Dec. 2009.

[12] Y. Qin, H. Chung, D. Y. Lin, and S. Y. R. Hui, “Current source ballast for high power lighting emitting diodes without electrolytic capacitor,” in *Proc. 34th Annual Conf. IEEE Ind. Electron.*, 2008, pp. 1968–1973.

[13] S. Y. R. Hui and Y. X. Qin, “A general photo-electro-thermal theory for light emitting diode (LED) systems,” *IEEE Trans. Power Electron.*, vol. 24, no. 8, pp. 1967–1976, Aug. 2009.

[14] H.-T. Chen, S.-C. Tan, and S. Y. R. Hui, “Color variation reduction of GaN-based white light-emitting diodes via peak-wavelength stabilization,” *IEEE Trans. Power Electron.*, vol. 29, no. 7, pp. 3709–3719, Jul. 2014.

[15] “ENERGY STAR Program Requirements for Solid State Lighting Luminaires, Eligibility Criteria - Version 1.1,” 2008. [Online]. Available: http://www.energystar.gov/index.cfm?c=new_specs.ssl_luminaires.

[16] “Electromagnetic Compatibility (EMC)—Part 3: Limits-Section 2: Limits for Harmonic Current

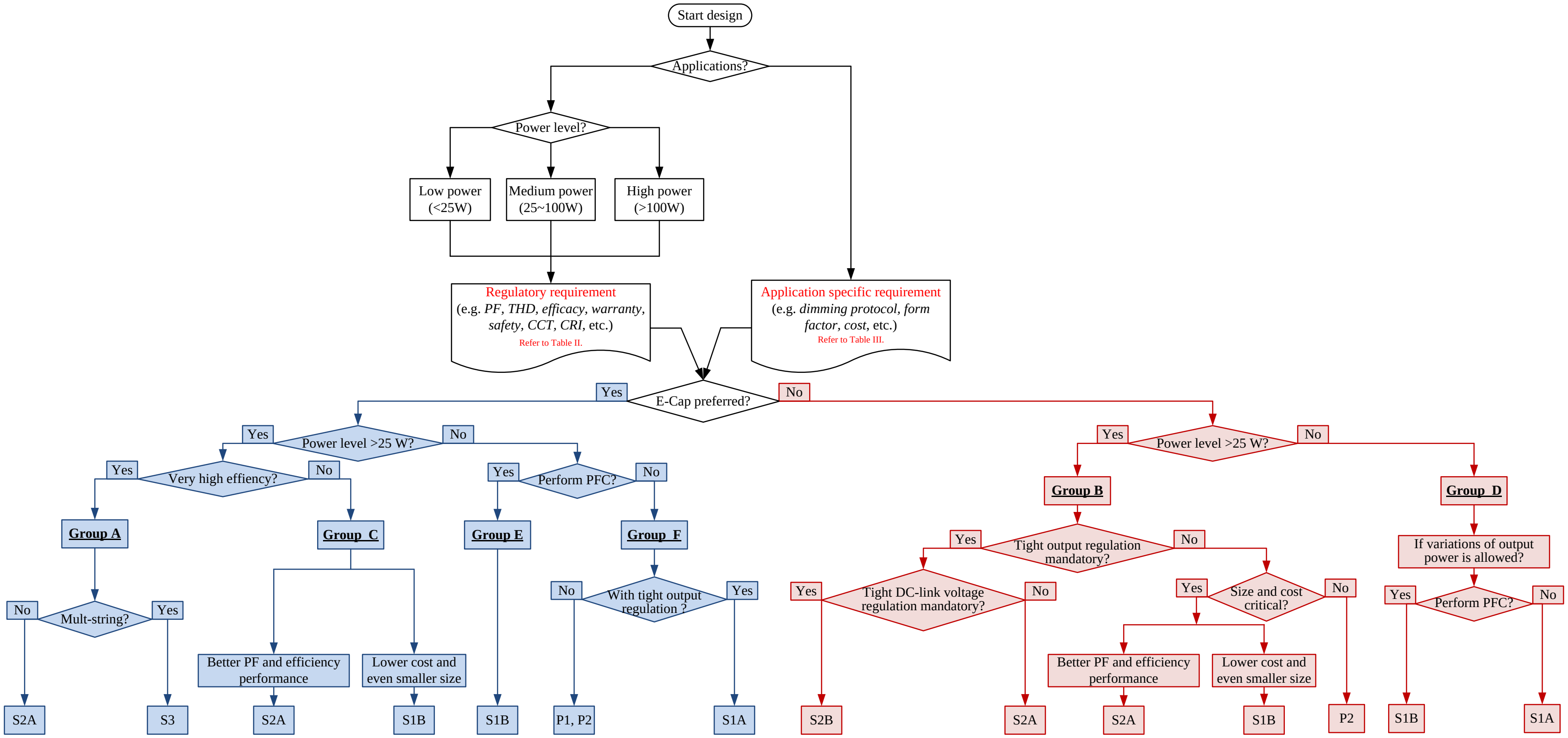

Fig. 16. An application-based LED driver design flow chart for selecting circuit topologies.

Emissions (Equipment Input Current < 16A Per Phase)," in *IEC1000-3-2*, 1995.

[17] Digikey, "LED Supplies." [Online]. Available: http://www.digikey.com/product-search/en?FV=fff40009,fff804be,8000e,8000f,80079,8007e,8007f,80081,800c7,800d0,802be,8048a,80727,8f40075,8f40077,8f40078,8f40079,8f4007a,8f4007b,8f4007d,8f4007e,8f4007f,8f40082,8f40084,8f4008d,8f400a9&mnonly=0&newproducts=0&ColumnSort=-1000011&page=1&stock=0&pbfree=0&rohs=0&quantity=&ptm=0&fid=0&pageSize=500.

[18] European Commission, *Low Voltage Directive 2006/95/EC*. 2006.

[19] U.S. Department of Energy, "Solid-State Lighting Research and Development: Manufacturing Roadmap," 2012.

[20] C.-J. Weng, "Advanced thermal enhancement and management of LED packages," *Int. Commun. Heat Mass Transf.*, vol. 36, no. 3, pp. 245–248, Mar. 2009.

[21] J. Zhou and W. Yan, "Experimental investigation on the performance characteristics of white LEDs used in illumination application," in *2007 IEEE Power Electron. Spec. Conf.*, 2007, pp. 1436–1440.

[22] M. Cai, K. M. Tian, W. B. Chen, H. Huang, H. Y. Tang, L. L. Liang, D. G. Yang, X. Fan, and G. Q. Zhang, "A novel hybrid method for reliability prediction of high-power LED luminaires," in *Proc. Int. Conf. Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*, 2013, pp. 1–5.

[23] M. Hodapp, "IESNA LM - 80 and TM - 21," in *Southeast Region Workshop*, 2011.

[24] Alliance for Solid-State Illumination Systems and Technologies (ASSIST), "ASSIST Recommends: LED Life for General

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2015.2417563, IEEE Transactions on Power Electronics

Lighting," 2005. [Online]. Available: http://www.lrc.rpi.edu/programs/solidstate/assist/.

[25] P. Wagner, "AC Line Dimming," *Powerbox USA*. [Online]. Available: http://www.powerbox.info/ssl/acLineDimming.asp.

[26] S. Y. Hui, S. N. Li, X. H. Tao, W. Chen, and W. M. Ng, "A novel passive offline LED driver with long lifetime," *IEEE Trans. Power Electron.*, vol. 25, no. 10, pp. 2665–2672, Oct. 2010.

[27] J. M. Alonso, S. S. Member, D. Gacio, A. J. Calleja, J. Ribas, and E. L. Corominas, "A Study on LED Retrofit Solutions for Low-Voltage Halogen Cycle Lamps," *IEEE Trans. Ind. Appl.*, vol. 48, no. 5, pp. 1673–1682, Sep. 2012.

[28] C. K. Lee, S. Li, and S. Y. R. Hui, "A design methodology for smart LED lighting systems powered by weakly regulated renewable power grids," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 548–554, Sep. 2011.

[29] W. Chen, S. N. Li, and S. Y. R. Hui, "A comparative study on the circuit topologies for offline passive light-emitting diode (LED) drivers with long lifetime & high efficiency," in *Proc. IEEE Energy Conv. Congr. Exp. (ECCE)*, 2010, pp. 724–730.

[30] S. Y. R. Hui, "Driver for LED lighting and method of driving LED lighting," PCT/CN2012/0849532012.

[31] R. A. Pinto, M. R. Cosetin, T. B. Marchesan, M. Cervi, A. Campos, and R. N. do Prado, "Compact lamp using high-brightness LEDs," in *Proc. IEEE Ind. Appl. Society Ann. Meeting*, 2008, pp. 1–5.

[32] F. Cacciotto, "Off-line constant current LEDs driver using the HVLED primary controller," in *Proc. 36th Ann. Conf. IEEE Ind. Electron. Soc.*, 2010, pp. 2601–2605.

[33] J. Ni, F. Zhang, Y. Yu, C. Gong, and X. Deng, "High power factor, low voltage stress, LED driver without electrolytic capacitor," in *Proc. Int. Conf. Power Engineering, Energy and Electrical Drives*, 2011, pp. 1–6.

[34] T. Kurachi, M. Shoyama, and T. Ninomiya, "Analysis of ripple current of an electrolytic capacitor in power factor controller," in *Proc. Int. Conf. Power Electron. Drive Syst. (PEDS)*, 1995, pp. 48–53.

[35] Y. Y.-C. Li and C.-L. C. Chen, "A novel single-stage high-power-factor AC-to-DC LED driving circuit with leakage inductance energy recycling," *IEEE Trans. Ind. Electron.*, vol. 59, no. 2, pp. 793–802, Feb. 2012.

[36] J. M. Alonso, J. Vina, D. G. Vaquero, G. Martinez, and R. Osorio, "Analysis and design of the integrated double buck–boost converter as a high-power-factor driver for power-LED lamps," *IEEE Trans. Ind. Electron.*, vol. 59, no. 4, pp. 1689–1697, Apr. 2012.

[37] T.-J. Liang, S.-M. Chen, L.-S. Yang, J.-F. Chen, and A. Ioinovici, "A single switch boost-flyback DC-DC converter integrated with switched-capacitor cell," in *Proc. Int. Conf. Power Electronics - ECCE Asia*, 2011, pp. 2782–2787.

[38] D. Lamar and M. Fernandez, "Tapped-inductor buck HB-LED AC–DC driver operating in boundary conduction mode for replacing incandescent bulb lamps," *IEEE Trans. Power Electron.*, vol. 27, no. 10, pp. 4329–4337, Oct. 2012.

[39] X. Qu, S. C. Wong, and C. K. Tse, "Resonance-assisted buck converter for offline driving of power LED replacement lamps," *IEEE Trans. Power Electron.*, vol. 26, no. 2, pp. 532–540, Feb. 2011.

[40] Z. Y. Z. Ye, F. Greenfeld, and Z. L. Z. Liang, "A topology study of single-phase offline AC/DC converters for high brightness white LED lighting with power factor pre-regulation and brightness dimmable Feature," in *Proc. Ann. Conf. IEEE Ind. Electron. Soc.*, 2008, pp. 1961–1967.

[41] H. Ma, J.-S. Lai, Q. Feng, W. Yu, C. Zheng, and Z. Zhao, "A novel valley-fill SPEIC-derived power supply without electrolytic capacitor for LED lighting application," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 3057–3071, Jun. 2012.

[42] B. Wang, X. Ruan, K. Yao, and M. Xu, "A method of reducing the peak-to-average ratio of LED current for electrolytic capacitor-less AC-DC drivers," *IEEE Trans. Power Electron.*, vol. 25, no. 3, pp. 592–601, Mar. 2010.

[43] C. K. Tse, M. H. L. Chow, and M. K. H. Cheung, "A family of PFC voltage regulator configurations with reduced redundant power processing," *IEEE Trans. Power Electron.*, vol. 16, no. 6, pp. 794–802, 2001.

[44] D. G. Lamar, J. S. Zuniga, A. R. Alonso, M. R. Gonzalez, and M. M. H. Alvarez, "A very simple control strategy for power factor correctors driving high-brightness LEDs," *IEEE Trans. Power Electron.*, vol. 24, no. 8, pp. 2032–2042, Aug. 2009.

[45] M. A. D. Costa, G. H. Costa, A. S. dos Santos, L. Schuch, and J. R. Pinheiro, "A high efficiency autonomous street lighting system based on solar energy and LEDs," in *Proc. Brazilian Power Electron. Conf.*, 2009, pp. 265–273.

[46] K. Zhou, J. Zhang, S. Yuvarajan, and D. F. Weng, "Quasi-active power factor correction circuit for HB LED driver," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1410–1415, May 2008.

[47] J.-J. C. J.-J. Chen, B.-H. H. B.-H. Hwang, C.-M. K. C.-M. Kung, W.-Y. T. W.-Y. Tai, and Y.-S. H. Y.-S. Hwang, "A new single-inductor quadratic buck converter using average-current-mode control without

slope-compensation," in *Proc. IEEE Conf. Ind. Electron. Appl.*, 2010, pp. 1082–1087.

[48] H.-J. Chiu, Y.-K. Lo, J.-T. Chen, S.-J. Cheng, C.-Y. Lin, and S.-C. Mou, "A high-efficiency dimmable LED driver for low-power lighting applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 735–743, Feb. 2010.

[49] T.-J. Liang, S.-M. Chen, L.-S. Yang, J.-F. Chen, and A. Ioinovici, "Ultra-large gain step-up switched-capacitor DC-DC converter with coupled inductor for alternative sources of energy," *IEEE Trans. Circuits Syst.*, vol. 59, no. 4, pp. 864–874, 2012.

[50] S.-M. Chen, T.-J. Liang, L.-S. Yang, and J.-F. Chen, "A safety enhanced, high step-up DC-DC converter for AC photovoltaic module application," *IEEE Trans. Power Electron.*, vol. 27, no. 4, pp. 1809–1817, Apr. 2012.

[51] S.-M. Chen, T.-J. Liang, L.-S. Yang, and J.-F. Chen, "A boost converter with capacitor multiplier and coupled inductor for AC module applications," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1503–1511, Apr. 2013.

[52] W. Li, L. Fan, Y. Zhao, X. He, D. Xu, and B. Wu, "High-step-up and high-efficiency fuel-cell power-generation system with active-clamp flyback–forward converter," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 599–610, Jan. 2012.

[53] Q. Zhao and F. C. Lee, "High-efficiency, high step-up DC-DC converters," *IEEE Trans. Power Electron.*, vol. 18, no. 1, pp. 65–73, Jan. 2003.

[54] B. R. Lin and J. Y. Dong, "New zero-voltage switching DC-DC converter for renewable energy conversion systems," *IET Power Electron.*, vol. 5, no. 4, p. 393, 2012.

[55] R.-Y. Duan and J.-D. Lee, "High-efficiency bidirectional DC-DC converter with coupled inductor," *IET Power Electron.*, vol. 5, no. 1, pp. 115–123, 2012.

[56] Z. Zhang, M. Chen, W. Chen, C. Jiang, and Z. Qian, "Analysis and implementation of phase synchronization control strategies for bcm interleaved flyback microinverters," *IEEE Trans. Power Electron.*, vol. 29, no. 11, pp. 5921–5932, Nov. 2014.

[57] C.-J. Huang, Y.-C. Chuang, and Y.-L. Ke, "Design of closed-loop buck-boost converter for LED driver circuit," in *Proc. IEEE Ind. Commercial Power Systems Technical Conf.*, 2011, pp. 1–6.

[58] R. Dayal and L. Parsa, "Non-isolated topologies for high step-down offline LED driver applications," in *Proc. IEEE Applied Power Electron. Conf. Exp.*, 2012, pp. 988–993.

[59] Y.-T. Hsieh, B.-D. Liu, J.-F. Wu, C.-L. Fang, H.-H. Tsai, and Ying-Zong Juang, "A SEPIC LED driver with a hybrid dimming technique for road vehicles," in *Proc. 14th Euro. Conf. Power Electron. Appl.*, 2011, pp. 1–7.

[60] A. E. Demian, C. H. G. Treviso, C. A. Gallo, and F. L. Tofoli, "Non-isolated DC-DC converters with wide conversion range used to drive high-brightness LEDs," *no. Cccm. IEEE*, 2009, pp. 598–605.

[61] J. M. Alonso, J. Viña, D. Gacio, L. Campa, G. Martínez, and R. Osorio, "Analysis and design of the quadratic buck-boost converter as a high-power-factor driver for power-LED lamps," in *Proc. 36th Annu. Conf. IEEE Ind. Electron. Soc.*, 2010, pp. 2541–2546.

[62] D. Gacio, J. M. Alonso, A. J. Calleja, J. Garcia, and M. Rico-Secades, "A universal-input single-stage high-power-factor power supply for hb-leds based on integrated buck–flyback converter," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 589–599, Feb. 2011.

[63] C. Qiao and K. M. Smedley, "A topology survey of single-stage power factor corrector with a boost type input-current-shaper," *IEEE Trans. Power Electron.*, vol. 16, no. 3, pp. 360–368, May 2001.

[64] X. Wu, J. Yang, J. Zhang, and Z. Qian, "Variable on-time (VOT)-controlled critical conduction mode buck PFC converter for high-input AC/DC HB-LED lighting applications," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4530–4539, Nov. 2012.

[65] B.-C. Kim, K.-B. Park, C.-E. Kim, B.-H. Lee, and G.-W. Moon, "LLC resonant converter with adaptive link-voltage variation for a high-power-density adapter," *IEEE Trans. Power Electron.*, vol. 25, no. 9, pp. 2248–2252, Sep. 2010.

[66] S. Wang, X. Ruan, K. Yao, S.-C. Tan, Y. Yang, and Z. Ye, "A flicker-free electrolytic capacitor-less AC–DC LED driver," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4540–4548, Nov. 2012.

[67] P. T. Krein, R. S. Balog, and M. Mirjafari, "Minimum energy and capacitance requirements for single-phase inverters and rectifiers using a ripple port," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4690–4698, Nov. 2012.

[68] S. Li and S. Y. R. Hui, "Variants of current-mirror circuits for reducing current imbalance in parallel LED strings," in *Proc. IEEE Energy Conv. Congr. Exp. (ECCE)*, 2012, pp. 3562–3567.

[69] S. Li, W. X. Zhong, W. Chen, and S. Y. R. Hui, "Novel self-configurable current-mirror techniques for reducing current imbalance in parallel light-emitting diode (LED) strings," *IEEE Trans. Power Electron.*, vol. 27, no. 4, pp. 2153–2162, Apr. 2012.

[70] S. Li and S. Y. R. Hui, "Self-configurable current-mirror circuit with short-circuit and open-circuit fault tolerance for balancing parallel light-emitting diode (LED) string currents," *IEEE Trans. Power Electron.*, vol. 29, no. 10, pp. 5498–5507, Oct. 2014.

[71] B. Williams, *Power Electronics: Devices, Drivers, Applications, and Passive Components*, Second Edition, McGraw-Hill, 1992, Chapter 10, p. 229.

[72] R. Zhang and H. S.-H. Chung, “Transformer-isolated resonant driver for parallel strings with robust balancing and stabilization of individual LED current,” in *Proc. IEEE Appl. Power Electron. Conf. Exp. (ECCE)*, 2014, pp. 1370–1377.

[73] R. Zhang and H. S.-H. Chung, “Daisy-chain transformer structure for current-balancing multiple LED strings,” in *Proc. IEEE Energy Conv. Congr. Exp. (ECCE)*, 2013, pp. 3118–3125.

[74] R. Zhang and H. S.-H. Chung, “Use of daisy-chained transformers for current-balancing multiple LED strings,” *IEEE Trans. Power Electron.*, vol. 29, no. 3, pp. 1418–1433, Mar. 2014.

[75] K. I. Hwu and S.-C. Chou, “A simple current-balancing converter for LED lighting,” in *Proc. IEEE Appl. Power Electron. Conf. Exp.*, 2009, pp. 587–590.

[76] R. Zane, “LED driver circuit with series-input-connected converter cells operating in continuous conduction mode,” *IEEE Trans. Power Electron.*, vol. 25, no. 3, pp. 574–582, Mar. 2010.

[77] W. Chen and S. Y. R. Hui, “A dimmable light-emitting diode (LED) driver with mag-amp postregulators for multistring applications,” *IEEE Trans. Power Electron.*, vol. 26, no. 6, pp. 1714–1722, Jun. 2011.

[78] A. Wilkins, J. Veitch, and B. Lehman, “LED lighting flicker and potential health concerns: IEEE standard PAR1789 update,” in *Proc. IEEE Energy Conv. Congr. Exp. (ECCE)*, 2010, pp. 171–178.

[79] B. Lehman, A. Wilkins, S. Berman, M. Poplawski, and N. J. Miller, “Proposing measures of flicker in the low frequencies for lighting applications,” in *Proc. IEEE Energy Conv. Congr. Exp. (ECCE)*, 2011, pp. 2865–2872.

[80] Institution of Engineering and Technology, *Code of Practice for the Application of LED Lighting Systems*. Institution of Engineering and Technology, 2014.

[81] http://fairchildsemi.co.kr/applications/lighting/led-lighting/

[82] Martin LaMonica, “Cree engineers a cheaper LED bulb by losing the heat sink”, IEEE Spectrum, 28 October, 2014.