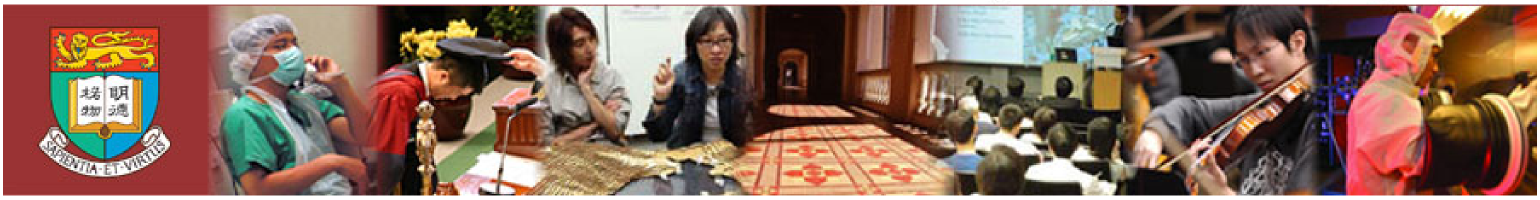

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A Review and Classification of LED Ballasts

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***Abstract*—This paper presents a review on existing ballasts for light-emitting diodes (LED) with considerations to their compliance to regulations, technological challenges, and on meeting various application requirements. All existing LED ballasts, including those proposed in recent literature, have been appropriately classified and systematically organized for the discussion. The dissemination of this information and its understanding is helpful for future R&D pursuits in this area.**

I. Introduction

Light-emitting diodes (LED) are widely considered as the future generation of light source for their superior properties over traditional light sources. Major applications of LED include vehicle lights, domestic lighting and decoration, street lighting, LCD backlight, and traffic signs, etc. [1]. Studies show that the rapid adoption of LED is attributed to their virtues of:

1. Inheriting a preponderant long lifetime of up to 100,000 hours when operated at appropriate operating conditions [2]–[5];
2. Being environmentally friendly since they are fabricated on mercury-free, recyclable semiconductor materials [5]–[8];
3. Having very high luminous efficacy of more than 150 lm/W [9], [10];
4. Being able to provide multi-color output that makes LED applications more flexible and diverse [11], [12].

Despite these advantages, LED are relatively fragile devices that they are highly sensitive to electrical, thermal, and photonic variations [3], [4], [6], [7], [13]. For example, a slight voltage variation across LED devices could cause a huge fluctuation in LED current and consequently light emission due to their diode-like *V-I* characteristics. Hence, proper driving method and control must be adopted. Another issue of concern is that LED are thermally sensitive and that their light output varies with ambient temperature. It is shown that under free convention, actual output lumen can be decreased even if LED power increases [13].

A good LED system design should take into consideration the basic factors that influence the actual performance and lifetime of LED devices. This will introduce additional requirements on the design and pose new challenges especially when cost, size, and reliabilities are of concern. Many regulations have been raised to stipulate the minimum requirements for HB-LED luminaries in general lightings. Among them, the *Energy Star Program* and *IEC Standards* are most widely adopted [14], [15].

Collectively, the major issues-of-concern in designing LED ballasts that designers should be aware of are as follows.

1. Engaging a proper driving mode with consideration to LED's efficacy, lifetime, temperature and applications. Possible driving methods include (i) amplitude mode (constant current); (ii) PWM mode (switching between constant current and zero current); (iii) *n*-level PWM mode [8] (switching between two or more constant current levels); (iv) DC current with a large ripple component, etc.
2. The ballast to be robust and durable, and to have a long lifetime that is compatible with the LED. Currently, the electrolytic capacitors (E-Caps) have been widely considered as the critical component that is affecting the system's lifetime [1], [3], [4], [16]–[18]. Yet, it must be emphasized that other factors such as system's operating temperature, voltage and current stresses on devices, etc., are equally important in preserving the system's lifespan.
3. A ballast to provide a current source output at a high-efficiency with tight control against any possible system variations. These variations include the change of LED dynamic equivalent resistance, ambient temperature, unexpected short/open circuit fault, etc.
4. Input current total harmonic distortion (THD), power factor (PF), and electromagnetic interference (EMI) level to meet *Energy Star* and *IEC standards* [14], [15]. For instance, *IEC standards for LED luminaires* have specified requirements on input current harmonics for different power levels (Class C for >25W, Class D for <25W).
5. Color temperature and chromaticity to comply *Energy Star Program*, which proposed that chromaticity variation should be less than 0.007 and chromaticity variation in different directions be less than 0.004 [14].
6. Galvanic isolations to be provided for high voltage applications according to *IEC standard* (EN 62031, EN 61347 part 2-13).
7. For indoor applications, such as general lighting, ballasts should be compact, low cost, and of minimal component counts.
8. For outdoor applications, such as street lighting illumination, ballast reliability and protection against lightning strike is critical since maintenance and parts replacement is labor-intensive and costly.

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9. For high power applications, parallel connection of multi-LED-strings is very common, and good current sharing must be assured if adopted [19], [20].

Other than serving as a design guide, the aforementioned points also set up the important criteria that will be used in this paper to evaluate the respective performances of different ballasts. This is because numerous LED ballasts with miscellaneous topologies have been proposed and it is confusing as to which topology should be applied on a given application. Therefore, in this paper, a systematic classification of the ballasts is provided and comparison based on the classification and the criteria mentioned above will be reported. The aim is to enhance the understanding and clarity of the subject and to make practical designs more organized and rational.

II. Ballast Classification and Evaluation

In this work, topologies are first categorized into passive LED ballasts and switched-mode LED ballasts based on whether they perform high-frequency switching operation. Passive (P) ballasts do not perform high-frequency switching operation and are thus more reliable and simple. However, they suffer from either being lossy or being bulky, and are incapable of providing output current regulation, which limits their applications. Alternatively, switched-mode (S) ballasts operate at high frequency and can realize compact size, low power loss, and precise output regulation. These properties allow them to have a broader area of applications. They are, however, less reliable than passive ballasts. Both the passive and switched-mode LED ballasts are further sub-classified into various types according to their topological configurations.

A. *Passive LED Ballast*

Passive ballasts do not contain active switches, controllers and the associated 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. There are three main types of passive topologies, namely *Passive Type I* (P1), *Passive Type II* (P2), and *Passive Type III* (P3).

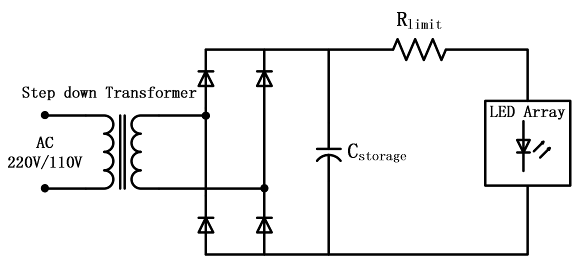

Fig. 1. Passive Type I (P1) LED ballast.

P1 ballasts are classified as one which utilizes a line frequency step-down transformer, a rectifier circuit with filter capacitor, and a current limiting resistor R_{limit} to convert the ac mains into a DC current source [21]. An example of P1 ballast is given in Fig. 1. To provide a smooth DC current to the LED, the required filter capacitor C is large as it is the only energy storage component between the pulsating input power and the constant DC output power. Moreover, to limit the flow of DC current from the capacitor to the LED, the required R_{limit} is not small, which introduces a significant power loss. Thus, P1 ballast is of low efficiency and by having no feedback control, its input current has high harmonic contents. In [21], it is shown the that power factor (PF) of such a circuit is very low and marginally satisfies the Class D limit.

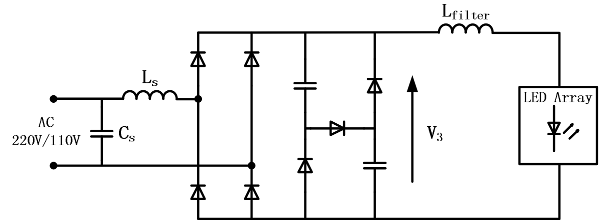

Fig. 2. Passive Type II (P2) LED ballast.

P2 ballasts, on the other hand, use ideally lossless impedance (inductor or capacitor) to limit the LED output current (see Fig. 2) [22]. Note that the valley-fill circuit in Fig. 2 can be entirely replaced by a non-E-cap. The impedance (inductive type) ωL_S withstands the voltage difference between the input voltage V_S and output voltage V_O, thereby eliminating the need for a low-frequency transformer. Also, this large input inductive impedance ωL_S can provide a smooth input current I_S even when the capacitor used at the DC side is very small. This eliminates the need of using electrolytic capacitors in the ballast, while concurrently achieving a good total harmonic distortion (THD) and EMI performance at the input side. For the P2 ballasts, a large filter inductor L_{filter} is required to convert the voltage source V_3 into a current source before driving the LED. P2 ballasts are highly efficient and their efficiency is comparable to that of switch-mode ballasts. With a simple PFC capacitor at the front end, it can offer excellent PF performance. However, it does not provide galvanic isolation between the supply side and the load side, and that the overall inductance required is large as compared to switch-mode ballasts.

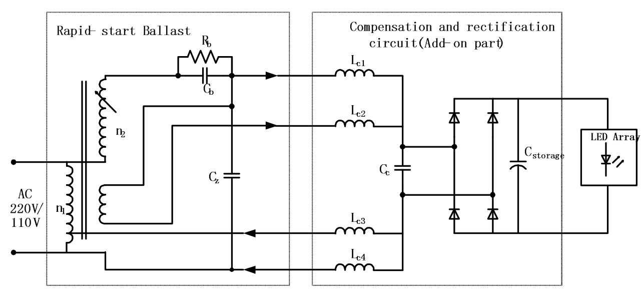

Fig.3 Passive Type III (P3) LED ballast.

P3 ballasts is one which comprises an add-on compensation LED circuit and a fluorescent rapid-start ballast [10] (see Fig. 3). The add-on compensation circuit and LED lamps can be directly fitted into any existing fluorescent ballast fixture without any modification [10]. The rapid-start ballast gives a well-shaped input current therefore achieving a high PF. However, the required magnetics for the compensation inductor is large and are of a similar size compared to that of P2 ballasts. Moreover, additional diode rectifying and filtering circuits are required since the output of the rapid-start ballast is AC. Also, the cascaded structure implies a lower efficiency as compared to P2 ballasts. Nevertheless, P3 ballasts are still an attractive solution for the near future as un-mounting and replacing the widely-existing fluorescent ballasts is a cost and time-consuming job, and add-on solutions are convenient and cost-effective.

TABLE I. COMPARISON BETWEEN VARIOUS TYPES OF PASSIVE (P1, P2, P3) LED BALLASTS

Ballast Type	Power Level	Efficiency	Total Capacitance	Inductance	THD satisfy	Volume & weight	Output current	Capacitance / Watt
P1	10.4 W	50%	4700 μF	Transformer $L_{Magnetizing}$=2.97 H	Class D	Heavy	DC	452 μF/W
P2	47 W	93.6%	40.3 μF	L_S = 1.47 H L_{filter} = 1.9 H	Class C	Heavy	DC	0.9 μF/W
P3	20 W	72.9%	50.3 μF	4 × 0.5 H	Class C	Heavy	DC	2.5 μF/W

Table I gives a comparison of the three passive LED ballasts, of which power level, efficiency, storage components, input current THD performances, etc., are listed and compared. It is evident that P2 ballasts can achieve the highest efficiency among the passive ballasts while satisfying the low input current THD limit. Since capacitors are of vital importance to the lifetime of LED ballasts, to evaluate the capacitance used in each topology for different power level, a normalized term given as Capacitance/Watt (capacitance per watt) is introduced in this paper. This parameter is a good indicator for telling what types of capacitors can be used. If the Capacitance/Watt is high, electrolytic capacitor (E-cap) has to be used since it has the highest capacitance density (capacitance per volume) such that a reasonably small ballast size can be achieved. Otherwise, non-E-cap is used. From Table I, it is shown that P2 ballasts have the lowest Capacitance/Watt (0.9 μF/W) among all the passive ballasts. With such a low Capacitance/Watt, non-E-cap can be applied.

At first glance, passive LED ballasts appear to be unappealing because of their bulky size and heavy weight. However, for most outdoor applications, space is not an issue. Without active switches and the associated controllers and external power supplies, and the possibility of avoiding E-Cap, passive LED ballasts provide a great option for outdoor applications such as street lighting, where system robustness and reliability are of prime concern. The ability to stand against lightning strikes is vital for these applications and passive LED ballasts are more prone to surviving from such strikes than switch-mode LED ballasts [22]. Nevertheless, as there is no output current regulation in passive LED ballasts, they are susceptible to unexpected situations (e.g. input voltage variation, load being short or open circuited). Thus, components should be optimized and protection circuit must be incorporated to alleviate these constraints. Also, passive ballasts are unable to provide dimming function, which is a desired feature of LED products. In multi-string applications, which are widely adopted in high power applications, additional current balancing circuits are necessary to enhance the overall system reliability [19], [20].

B. Switched-Mode LED Ballast

Switched-mode LED ballasts take advantage of high-frequency operation and active control of switches such that a small ballast size and precise output current regulation can be achieved to meet different applications, such as for general indoor lighting, dimming, color variations, circuit failure protection, etc. In contrast to passive LED ballasts, in switched-mode LED ballasts, active power factor correction (PFC), current sharing and load fault protection can all be easily implemented. These superior properties make them more attractive for applications. Recently, a vast variety of switched-mode LED ballast topologies have been proposed. These topologies can be classified on a functional basis as single stage (S1), two stages (S2), and three stages (S3), regardless if there is galvanic isolation in the converters.

1) Single-Stage Ballasts

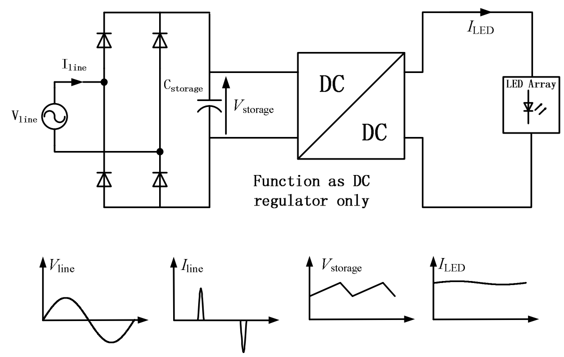

Fig. 4. Switched-mode single-stage Type A (S1A) ballast.

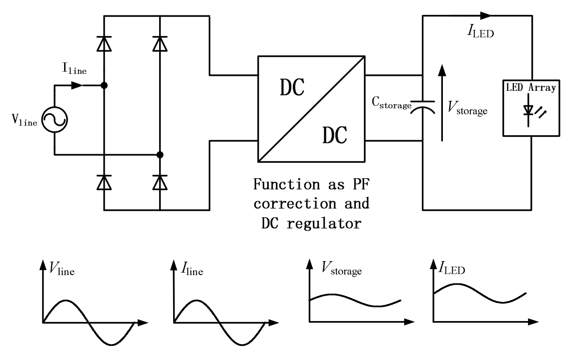

Fig. 5. Switched-mode single-stage Type B (S1B) ballast.

Switched-mode single-stage (S1) ballasts typically contain only one active switch in its circuit. Since it is necessary to concurrently perform both PFC and output current regulation functions through one power processing stage, it is often difficult to assure good performance such as high efficiency, good PF, and constant current output simultaneously. S1 ballasts are of compact size and are mainly for low power applications where size and cost are critical, such as in portable flashlight and LED bulbs, etc. High power applications have more stringent regulations which disqualify the use of S1 ballasts. According to IEC60001, the input harmonics requirement for luminaries with power level <25 W (Class D limits) is less stringent than that of >25 W (Class C limits). This eases the design of the PFC pre-regulator for low power applications. With this, the design challenge shifts to achieving high efficiency with high DC/DC conversion ratio in S1 ballasts since the targeting LED are of relatively low power.

There are two main types of S1 ballasts, namely Type A and Type B (see Figs. 4 and 5). Their core difference is the location of the storage capacitor. Fig. 4 illustrates the switched-mode single-stage Type A (S1A) ballast that has its storage capacitor at the low frequency side. This leads to a pulsating input current, which normally breeches regulations (shown in Fig.4 as I_{line}). A low-frequency EMI filter can be used to alleviate the distortion, but it increases cost and size. The low-frequency capacitor should be of large capacitance value to provide a smooth output voltage for the following DC/DC conversion process in achieving a well-regulated DC output. The output of S1A ballasts can be of small ripple content since the low-frequency storage capacitor is buffering the pulsating input power. Nevertheless, S1A ballasts are only applicable to portable, off-line, or low-power applications with very small output power, e.g. LED bulbs. In [23], [24], the output power is less than 5 W.

In switched-mode single-stage Type B (S1B) ballasts, the capacitor is placed at the high frequency side after the DC/DC converter, as illustrated in Fig.5. The single DC/DC converter in S1B ballasts operate simultaneously to achieve both PFC and output current regulation. Thus, the input current waveform of S1B ballasts is better shaped as compared to that of S1A ballasts. However, with S1B ballasts, the achievable efficiency is not that high since both PFC and DC regulation cannot be working simultaneously at the same optimal state that can give the highest possible power conversion efficiency. Moreover, even though the capacitor is placed at the high frequency side, the required capacitance cannot be significantly reduced as it has to handle both the high-frequency switching ripple as well as the low-frequency ripple caused by the pulsating input power and the constant output power. Therefore, S1B ballasts inherently contain low-frequency output current ripples and their capacitor sizes are similar to that of S1A.

Classical topologies including the buck [3], [25–27], buck-boost, SEPIC [28], [29], flyback [18], [30], half-bridge [31], and push-pull converters [32], etc., can all be used as S1B ballasts. PFC can also be performed passively with valley-fill circuits [33]. Note that S1B ballasts are more preferred than S1A ballasts in low power applications because the former can achieve better PF and lower EMI for similar count of component used and design specifications. As mentioned, the real challenge of S1 ballasts is to maintain a high efficiency with a large step-down ratio. Usually a larger step-down ratio means a shorter duty cycle. This not only makes precise control more difficult as operating frequency goes higher, but it also reduces overall system's efficiency. For example, for an S1 ballast that is based on a buck PFC converter with a 220 V, 50 Hz input and a 10 V, 500 mA output, the required duty cycle at the peak input voltage can be calculated as $D = 10/220\sqrt{2} = 0.032$. This is too small for practical applications. To realize a larger step-down conversion ratio, traditional single-stage topologies without galvanic isolation are modified to achieve higher efficiency and better control performance.

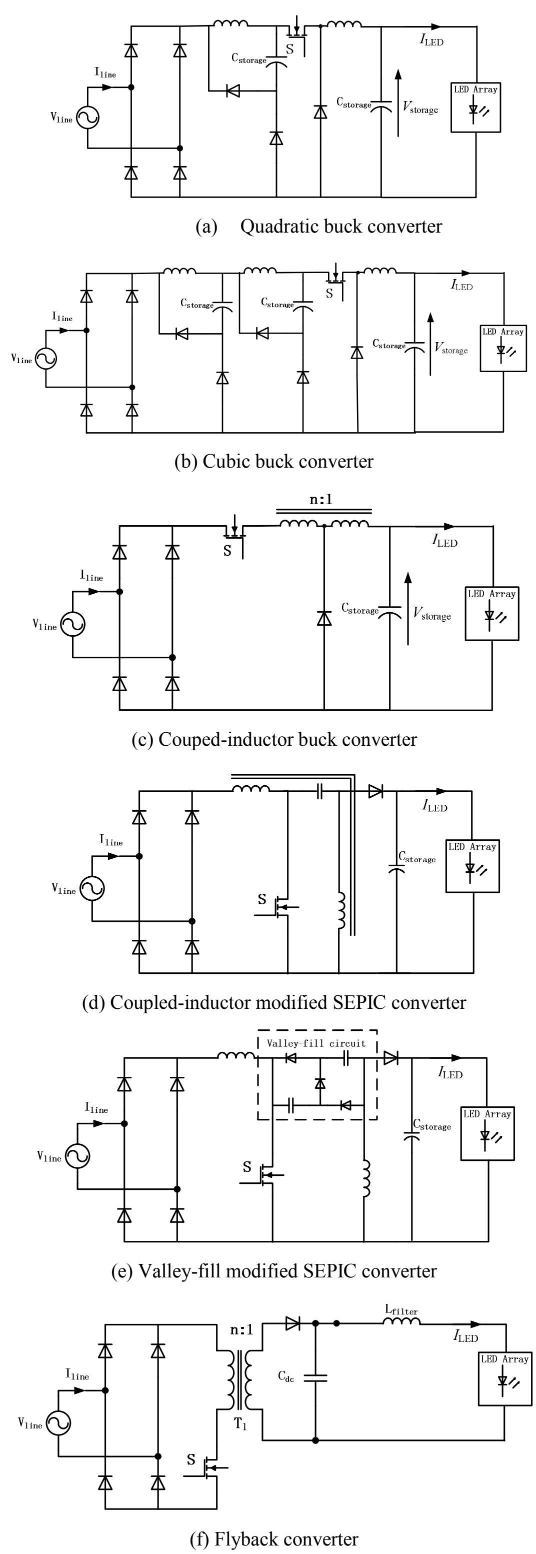

Fig. 6. Different kinds of single-stage topologies with a high step-down ratio. (a) quadratic buck converter, (b) cubic buck converter, (c) couped-inductor buck converter, (d) coupled-inductor modified SEPIC converter, (e) valley-fill modified SEPIC converter, and (f) flyback converter.

Topologies such as the quadratic buck and cubic buck converters (shown in Figs. 6(a) and 6(b)) are adopted to provide a high step-down conversion ratio with a reasonably practical value of the duty ratio [34]. Even though only one active switch is used, power efficiency in these kinds of single-stage converter is compromised since they are inherently a cascaded structure of several step-down converters and energy is processed several times through the circuit. Furthermore, the number of diodes, inductors, and capacitors will increase sharply as the required step-down ratio goes high. Other approaches, namely coupled-inductor assisted converters [25], [35], offer a simple solution to the high step-down ratio problem without over-sacrificing the efficiency and system complexity. Fig. 6(c) shows a coupled-inductor modified buck PFC converter that is similar to traditional buck PFC converter except that the original inductor has been replaced by a coupled inductor. This topology allows the setting of the duty cycle to be within what is practical via the design of the turns ratio of the coupled inductor *L*. For this topology, energy is not processed several times, as it is in quadratic and cubic buck converters. Hence, it inherently has a higher efficiency. Moreover, by re-circulating the leakage inductor energy of the coupled-inductor back into the circuit, efficiency could be further increased [36]. Fig. 6(d) shows the use of coupled-inductor in the SEPIC topology. Beside coupled-inductors, valley-fill circuits have also been incorporated into traditional converters to achieve a higher conversion ratio [29], [37]. Fig. 6(e) shows a modified SEPIC converter with valley-fill circuit. Note that both the valley-fill circuit and coupled-inductor can be concurrently applied to the same converter to achieve an even higher conversion ratio [38].

For topologies with galvanic (transformer) isolation, attaining a high conversion ratio is easy - through the design of the transformer's turns ratio. The focus is then on improving the overall efficiency. Of all topologies, the flyback topologies (see Fig. 6(f)) are most widely used because of their simple structure and high PF. The power loss in the transformer's leakage inductance can decrease the overall efficiency. This can be improved by re-circulating and reusing the leakage energy [39]. Table II lists some reported S1 types of ballasts. As discussed, for this kind of ballasts, a large capacitor is required to provide a smooth DC current.

2) *Two-Stage Ballasts*

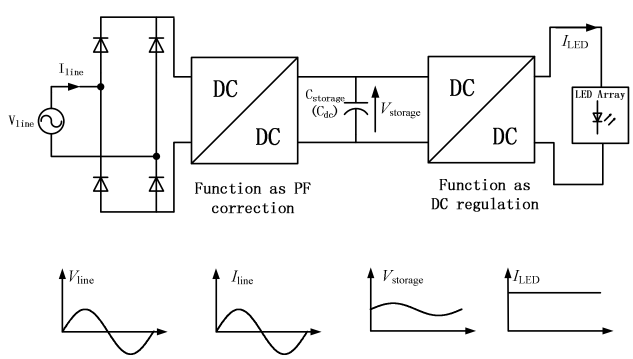

Fig. 7. Switched-mode two-stage Type A (S2A) ballast.

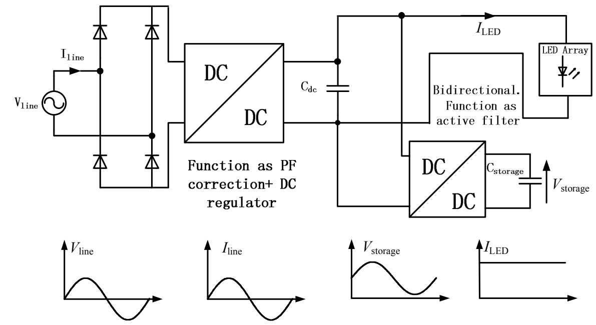

Fig. 8 Switched-mode two-stage Type B (S2B) ballast.

In two-stage (S2) ballasts, the PFC pre-regulator and DC/DC regulator are independent, and each stage can be individually optimized. Galvanic isolation can be incorporated in either stage. S2 ballasts offer excellent input current waveform with high efficiency, long lifetime, high reliability, little chromaticity variation, being easily dimmable, and have good safety control. These features are desired in LED systems of medium or high power applications, where cost and size is less of an issue as compared to system performances.

S2 ballasts can be classified into two types, namely Type A and Type B. For Type A (S2A) ballasts (see Fig. 7), the LED are connected to the output of the DC/DC converter, which is cascaded to a front-end PFC pre-regulator [3], [6], [7], [17], [39], [40]. Here, the DC/DC converter stage handles all the power from the PFC pre-regulator stage. For Type B (S2B) ballasts (see Fig. 8), the DC/DC converter is connected in parallel with the LED and handles only the instantaneous difference between the input and the output power [1], [4]. Therefore, it is expected that S2B ballasts achieve a higher efficiency and also a smaller output current ripple than S2A ballasts (under the assumption that both ballasts have the same output capacitance) since less power is processed. Furthermore, S2B topologies can be designed to achieve the lowest Capacitance/Watt value among all existing ballasts with DC current. This advantageous feature can eliminate the need for the E-cap and therefore offers a solution to improve the lifetime of the LED ballast.

For S2A ballasts, boost topologies are mostly adopted as the PFC pre-regulator due to their excellent input current waveform in terms of attaining high PF and low harmonic contents [3], [7], [17], [40]. They also give better efficiency at high power levels as compared to other topologies. For the continuous conduction mode operation, little or no EMI filter is required, which reduces cost and size. For the DC/DC conversion stage, the main task is to provide good output regulation at a high efficiency. If the PFC pre-regulator is of boost type, a large step-down DC/DC conversion is required since the output voltage of the pre-regulator is higher than the amplitude of the line input voltage. The problem of large step-down conversion in S2A ballasts is similar to that of S1 ballasts and therefore the same solutions can be applied. The main difference is that the requirement for large step-down ratio is less stringent on S2 ballasts since they are usually aimed at higher power applications. For such DC/DC conversion, many types of high-efficiency converters are available. With the output from the PFC pre-regulator being usually quite stable, the resonant converters will be highly suitable for the purpose. Also, the so-called twin-bus buck topology can be applied [29], [41], [42].

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

Isolation Type	Structures	High Step Down Ability?	High Efficiency?	Structures	High Step Down Ability?	High Efficiency?
Non-Isolated S1B	Buck-Boost	×	×	Coupled-Inductor Buck	√	√
	SEPIC	×	×	Coupled-Inductor SEPIC	√	√
	Resonant-Assist Buck	×	×	Valley-Fill Modified SEPIC	√	√
	Quasi-Active PFC with Buck	×	×	Quadratic and Cubic Buck	√	×
				Quadratic Buck-Boost	√	×
Isolated S1B	Flyback	√	×	Integrated Buck with Flyback	√	×
	Integrated Buck-Boost with Flyback	√	×	Integrated Boost with Forward	√	×
	Integrated Boost with Flyback	√	×			

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

Type	Stage Component	Capacitance/Watt	Stage Component	Capacitance /Watt
S2A	Boost (PFC) + Flyback (DC/DC)	2.5 μF/W	SEPIC (PFC)+ Twin-Bus Buck (DC/DC)	N.A.
	Boost (PFC) + LLC resonant (DC/DC)	0.04 μF/W (for C_{dc})	Any PFC + Capacitor Isolated resonant Ballast	N.A.
	Boost (PFC) + Asymmetrical HB (DC/DC)	N.A.		
	Boost (PFC) + Forward (DC/DC)	0.05 μF/W (for C_{dc})	Any PFC+ integrated buck-boost buck (DC/DC)	N.A.
	Buck (PFC) + current fed inverter (DC/DC)	1.44 μF/W	Any PFC + coupled-inductor buck (DC/DC)	N.A.
	Buck (PFC) + LLC resonant (DC/DC)	6.27 μF/W	Any PFC + Contactless Ballast (DC/DC)	N.A.
	Non-cascading boost resonant (PFC) + Buck (DC/DC)	91 μF/W	Flyback (PFC+DC/DC) + Buck (DC/DC)	N.A.
S2B	Flyback (PFC+DC/DC) + Bidirectional buck-boost converter	0.61 μF/W		
	Modified Flyback	0.96 μF/W		

Though the two stage operations of the S2A ballasts could be independently optimized, the overall system performance is still dependent on the combined effect of the two stages since they mutually affect one another. Designing and optimizing such a system for different applications and power levels is no doubt tedious and time-consuming, which requires expert knowledge and experience on such system design.

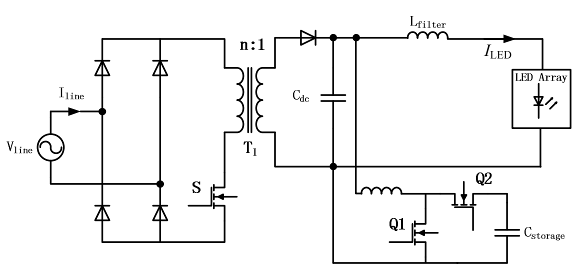

Fig. 9. An S2B ballast.

S2B ballasts, on the other hand, do not possess the aforementioned design difficulty. In S2B ballasts, the DC/DC conversion stage is placed in parallel with the load. This introduces new properties and improvement as compared to S2A ballasts [1], [4]. Its DC/DC stage serves not as an output current regulator but as an active filter. The output regulation is done in the first stage, which means that the first-stage converter performs concurrently the PFC and the DC/DC regulation similar to that of S1B ballasts. An example of an S2B ballast is shown in Fig. 9, which is a PFC flyback converter plus a bidirectional buck-boost converter [1]. The PFC flyback converter in the first stage is a conventional single-stage PFC converter with isolation, and the bidirectional converter in the second stage is actively controlled to handle the instantaneous difference between the pulsating input power and the constant output power. This power difference is stored at the output of bidirectional converter $C_{storage}$, of which voltage is intentionally designed to have a large fluctuation such that only a small capacitance is required to handle the same pulsating power. In [1], the Capacitor/Watt for the storage capacitor $C_{storage}$ and DC-link capacitor C_{dc} are respectively 0.0139 μF/W and 0.6 μF/W, which are much smaller than all other topologies with the same designed specifications. This allows non-E-cap to be adopted as the storage capacitor in the S2B ballasts. Additionally, by having only the pulsating portion of the total input energy processed by both the converters, while the remaining constant portion processed only by the first-stage converter before being delivered to the LED, S2B ballasts is expectedly of a higher efficiency than S2A ballasts. In addition, the design of S2 ballasts is relatively easy. This idea of active filtering is applicable to any S1B ballasts to form new kinds of S2B ballasts.

Table III lists some of the reported S2 types of ballasts. It can be clearly seen that S2B ballasts can achieve the lowest value of Capacitance/Watt. For S2A ballasts, there are cases where some ballasts are designed with a similarly low value of Capacitance/Watt. This is achievable at the expense of sacrificing the output current driving the LED, which is no longer a constant current, but contains a large second-harmonic ripple which will lead to flickering of the emitted light from the LED.

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

Type of Post-Regulator	Component in each post regulator	Comments
Linear Type	BJT transistor	DC output current. Simple structure, but with lower efficiency. Therefore, need to adaptively change the output voltage of the 2nd stage to improve efficiency. Dimming method - Amplitude Mode.
	MOSFET	
	Current mirror based circuit	
Switch Type	BJT transistor	PWM pulsating output current. Simple structure and higher efficiency than linear type. Dimming method - PWM or Phase-Shift PWM Mode.
	MOSFET	
DC/DC Converter Type	Twin-bus buck	DC output current. Higher efficiency. Dimming method - Amplitude Mode.
	Buck-boost	DC output current. Converters are with series-input parallel-output structure. With one common Duty Cycle command, inherent current sharing and open/short circuit fault protection can be achieved. Dimming method - Amplitude Mode.
	Multiple transformer after a common *LLC* (2nd stage)	
	Coupled inductor after a common cap isolated ballast (2nd stage)	DC output current. Inherent current sharing abilities. Dimming method - Amplitude Mode.
	Mag-amp assisted rectifier after a common Forward (2nd stage)	DC output current. Simple structure compared to other DC/DC converter types of post-regulators with high efficiency. Dimming method - Amplitude Mode.

3) *Three-Stage Ballasts*

Three-stage (S3) ballasts are targeted at multi-string LED applications. The first two stages of the S3 ballasts are made up of a regular S2 ballast, and the third stage is a current post-regulator that provides even current sharing among individual LED string and can be functioned to perform dimming control of the LED. The cost and component counts of the post-regulator increases 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. For linear-type post-regulators, the task is to provide a DC constant (amplitude mode) and equal output current to each LED string. For this purpose, either BJTs operating in the linear region or current-mirror based circuits can be adopted for their simple implementation and low cost at the expense of a lower efficiency [19]. Among various methods, the recently proposed reconfigurable current mirror circuits, which are free of auxiliary power supplies and controllers, and inherit good robustness and durability, are found to be highly promising for such tasks [19], [20]. Unlike other current balancing and dimming methods, these methods are applicable to both passive and switched-mode LED ballasts.

The DC/DC converter type of post-regulators operate similarly to the linear-type post regulators in providing a DC current to the LED (amplitude mode), but with higher reliability and efficiency since such post-regulators are operated as switched-mode current sources. The tradeoff of this solution is that it is highly cost ineffective to apply one post-regulator to each individual LED string. One possible solution is to adopt the single-input-multiple-output topologies to serve both as the second stage converter as well as the post-regulators, thereby eliminating the need for additional post-regulator circuit [44]. Current sharing is easily achieved through a common control signal. In [45], the mag-amp, which is a highly efficient device that has a simpler structure compared to the multiple-output converter topologies, is incorporated as the post-regulator to achieve current sharing.

For the switch-type post-regulators, either the BJT or MOSFET is used in each string to work as PWM switches for controlling the duty cycle of the LED current (PWM mode), which in this case is of PWM rectangular-pulsating current waveform. This kind of post-regulators gives better control of the dimming applications as compared to those based on amplitude mode since in this regulator, the average value of the PWM rectangular-pulsating current varies linearly with the duty cycle, and that it is easy to achieve precise control of the duty cycle and thus the average current. On the other hand, with the amplitude mode, precise tracking of the DC current amplitude through the control of the voltage output is more difficult because of the diode-like *V-I* characteristics of LED. Furthermore, the power loss of transistors that results from the linear regulation process of the linear-type post-regulators is absent in the switch-type post-regulators. Therefore, the latter is more efficient in regulating the current than the former. However, it must be noted that with the PWM mode, the output lumen is lower than that of the amplitude mode, especially if the junction temperature of the LED is high [8]. Hence, there should be a balance in consideration on both current regulation efficiency and light output efficacy in the selection of the post-regulators when the overall system efficiency is of a concern.

Table IV lists various types of the current post-regulators of S3 ballasts reported in the literature.

III. CONCLUSIONS

A thorough survey of the existing works on LED ballasts and their related technologies with considerations to their compliance to regulations, technological challenges, and on meeting various application requirements, has been conducted and discussed in this paper. In particular, the ballasts have been systematically classified into the passive (P) types and the switched-mode (S) types, and then sub-classified respectively into Types P1, P2, P3 and Types S1, S2, S3 according to their topological configurations. An important parameter known as Capacitance/Watt, which is useful for evaluating if the ballast is well designed in terms of having a smaller capacitance requirement, is suggested in this paper for future adoption.

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REFERENCES

[1] 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. on Power Electronics*, vol. 27, no. 11, pp. 4540–4548, Nov. 2012.

[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. on Power Electronics*, vol. 26, no. 7, pp. 1820–1825, 2011.

[3] 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., IEEE IECON*, 2008, pp. 1968–1973.

[4] W. Chen and S. 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. on Power Electronics*, vol. 27, no. 3, pp. 1598–1607, Mar. 2012.

[5] W. Chen and S. Y. R. Hui, "A dimmable light-emitting diode (LED) driver with mag-amp postregulators for multistring applications," in *Proc., IEEE IECON*, 2010, vol. 26, no. 6, pp. 2523–2528.

[6] 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. on Power Electronics*, vol. 27, no. 11, pp. 4530–4539, 2012.

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

[8] S. C. Tan, "General *n*-level driving approach for improving electrical-to-optical energy-conversion efficiency of fast-response saturable lighting devices," *IEEE Trans. on Ind. Electronics*, vol. 57, no. 4, pp. 1342–1353, Apr. 2010.

[9] M. Arias, A. Vazquez, and J. Sebastián, "An overview of the AC-DC and DC-DC Converters for LED lighting applications," *Automatika − Journal for Control, Measurement, Electronics, Computing and Communications*, 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., IEEE ECCE Asia*, 2011, pp. 507–514.

[11]Y. Lo, K. Wu, K. Pai, and H. Chiu, "Design and implementation of RGB LED drivers for LCD backlight modules," *IEEE Trans. on Industrial Electronics*, vol. 56, no. 12, pp. 4862–4871, 2009.

[12] "Philips HUE." [Online]. Available: http://www.meethue.com/en-US.

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

[14]"Program requirements for solid-state lighting luminaires: eligibility criteria—version 1.1, Revised, ENERGY STAR," Washington, DC.

[15] "Electromagnetic compatibility (EMC)—part 3: limits-section 2: limits for harmonic current emissions (equipment input current < 16A per phase), " IEC1000-3-2, 1995.

[16] E. Rifa, "Electrolytic capacitors application guide," [Online] Available: *www. evox-rifa. com*, 2001.

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

[18] 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. on Power Electronics*, vol. 25, no. 3, pp. 592–601, 2010.

[19] S. N. 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. on Power Electronics*, vol. 27, no. 4, pp. 2153–2162, Apr. 2012.

[20] S. Li and S. Y. Hui, "Variants of current-mirror circuits for reducing current imbalance in parallel LED strings," in *Proc., IEEE ECCE*, 2012, pp. 3562–3567.

[21] J. M. Alonso, 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. on Industry Applications*, vol. 48, no. 5, pp. 1673–1682, Sep. 2012.

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

[23] R. A. Pinto, M. R. Cosetin, T. B. Marchesan, M. Cervi, A. Campos, and R. N. do Prado, "Compact lamp using high-brightness LEDs," *Proc., IEEE IAS*, 2008, pp. 1–5.

[24] F. Cacciotto, "Off-line constant current LEDs driver using the HVLED primary controller," in *Proc., IEEE IECON*, 2010, pp. 2601–2605.

[25] 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. on Power Electronics*, vol. 27, no. 10, pp. 4329–4337, Oct. 2012.

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

[27] J. Alonso and J. Vina, "Analysis and design of the integrated double buck–boost converter as a high-power-factor driver for power-LED lamps," *IEEE Trans. on Industrial Electronics*, vol. 59, no. 4, pp. 1689–1697, 2012.

[28] 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," in *Proc. IEEE IECON*, 2008, pp. 1961–1967.

[29]H. Ma, J. Lai, Q. Feng, and W. Yu, "A novel valley-fill SEPIC-derived power supply without electrolytic capacitor for led lighting application," *IEEE Trans. on Power Electronics*, vol. 27, no. 6, pp. 3057–3071, 2012.

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

[31]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. on Power Electronics*, vol. 24, no. 8, pp. 2032–2042, 2009.

[32] 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 Electronics Conference*, 2009, pp. 265–273.

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

[34] J. -J. Chen, B.-H. Hwang, C. -M. Kung, W. -Y. Tai, and Y.-S. Hwang, "A new single-inductor quadratic buck converter using average-current-mode control without slope-compensation," *in Proc., IEEE ICIEA,* 2010, pp. 1082–1087.

[35] H. Chiu, Y. Lo, and J. Chen, "A high-efficiency dimmable LED driver for low-power lighting applications," *IEEE Trans. on Industrial Electronics*, vol. 57, no. 2, pp. 735–743, 2010.

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

[37]B. Axelrod, Y. Berkovich, and A. Ioinovici, "Switched-capacitor/ switched-inductor structures for getting transformerless hybrid DC-DC PWM Converters," *IEEE Trans. on Cir. and Sys.*, vol. 55, no. 2, pp. 687–696, 2008.

[38] 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. on Circuits and Systems*, vol. 59, no. 4, pp. 864–874, 2012.

[39] 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. on Industrial Electronics*, vol. 59, no. 2, pp. 793–802, Feb. 2012.

[40] 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. on Power Electronics*, vol. 25, no. 9, pp. 2248–2252, Sep. 2010.

[41] 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. on Industry Applications*, vol. 49, no. 1, pp. 127–137, 2013.

[42] H. Ma, W. Yu, C. Zheng, J. J. Lai, Q. Feng, and B. Chen, "A universal-input high-power-factor PFC pre-regulator without electrolytic capacitor for PWM dimming LED lighting application," in *Proc., IEEE ECCE*, 2011, pp. 2288–2295.

[43] 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. on Power Electronics*, vol. 27, no. 11, pp. 4540–4548, Nov. 2012.

[44] Q. Hu and R. Zane, "LED driver circuit with series-input-connected converter cells operating in continuous conduction mode," *IEEE Trans. on Power Electronics*, vol. 25, no. 3, pp. 574–582, Mar. 2010.

[45] W. Chen and S. Y. R. Hui, "A dimmable light-emitting diode (LED) driver with cascaded mag-amp postregulators for multistring applications," in *Proc., IEEE IECON*, 2010, pp. 2523–2528.