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A Comprehensive Review on Recent Developments of LED Drivers

[1]M. J. Ang, [2]Nadia M. L Tan, [3]Johnny S. P. Koh, [4]Rodney H. G. Tan

[1]Advenxus Solutions Sdn. Bhd., Technical Department, Bandar Puteri Puchong, Puchong, Malaysia.
[2]Universiti Tenaga Nasional, Department of Electrical Power Engineering, Jalan IKRAM-UNITEN, Kajang, Malaysia.
[3]Universiti Tenaga Nasional, Department of Electronics and Communications Engineering, Jalan IKRAM-UNITEN, Kajang, Malaysia.
[4]UCSI University, Department of Electrical and Electronics Engineering, Faculty of Engineering, Technology and Built Environment, Kuala Lumpur, Malaysia.

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ABSTRACT

Background: In these recent years, LED lighting has been widely implemented for household and industrial applications. By implementing the correct topology, the performance of a LED driver can be improved in terms of efficiency, power factor, lifespan, size and cost of development. **Objective:** This paper aims to provide a comprehensive review on the latest trends of LED driver design to serve as a useful guide for design engineers and researchers. **Result:** Latest research journals and conference proceedings have been reviewed. **Conclusion:** There are suitable converter topologies for LED drivers of varied power levels, with the flyback converter being the most suitable for applications of less than 100W. When designing the LED driver, considerations must be made on the power factor, efficiency, dimming capability, and lifespan.

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INTRODUCTION

In year 1962, the first commercial light-emitting diode (LED) was commonly used as a replacement for neon indicator lamp as well as in seven segment display. It is also the first technology implemented in expensive laboratory electronics test equipment. Following which the LED was employed in television, radio, and etc. In 1972, a special high brightness LED had been invented for fibre optic use in transmitting data. In these recent few years, the improvement of the High-brightness LED (HBLED) has taken the lead in the development of lighting system by combining multiple HBLEDs as light source.

An LED driver comprises of a power electronics circuit which converts the Alternating Current (AC) incoming power source into a Direct Current (DC) output power source. Thus, it plays a major role in supplying a suitable and controllable DC power source for LED lighting as LEDs can only be powered up by DC power source only. Many research and effort have been carried out to improve the performance of LED driver in terms of higher efficiency and longer reliability.

LED technology has offered a vast amount of advantage such as longer lifetime, higher luminous efficiency, and energy-conversion efficiency as well as better colour property. These attractive characteristic of LED have offered an ideal alternative light source to the conventional light source in

Table 1: Comparison of Incandescent Bulb, CFL and LED.

Lighting Type	Incandescent	CFL	LED
Lifespan (hrs)	1 000 – 3000	8 000 – 15 000	25 000 – 45 000
Lifespan (years)	0.9	9.1	22.8
Power consumption (W)	60	13	12.5
Lumens (lm)	640	900	800
Luminous efficacy (lm/W)	10.67	69.23	64
Colour Temperature (K)	2 790	2 700	2 700

Various applications (Lin and Chen, 2012). Currently, most of the electronics products such as liquid-crystal-display (LCD) backlighting, general purpose lighting, street lighting, traffic light, and vehicle lighting system have started to implement LED technology because of its attractive characteristics. The requirements of the LED driver for each application are different.

Corresponding Author: Nadia M. L. Tan., Universiti Tenaga Nasional, Department of Electrical Power Engineering, Jalan IKRAM-UNITEN, 43000, Kajang, Malaysia.
E-mail: nadia@uniten.edu.my

This paper presents the latest trends of the LED driver by reviewing the various applications and driver circuit components of the LED driver. It also discusses the improvements on the LED drivers in terms of power factor, efficiency, harmonic reduction, dimming capability, and prolonged lifespan.

2.0 LED Driver Applications

General Lighting (Indoor Lighting):

Table 1 presents some important specifications of incandescent bulb, compact fluorescent lamp (CFL) and LEDs which are available in the market in year 2012 (Philip Lightings, 2012). It can be observed that CFL offers the advantages of longer lifetime and higher luminous efficacy in comparison with the incandescent light bulb. Hence, historically, CFL has become the primary electric-powered light source for general indoor lighting application. However, CFL achieves this high efficacy by utilizing the optical properties of mercury vapor. Thus, CFL is not environmental friendly as it cannot be recycled and consists of mercury in it (Hassan and Ang, 2011). Due to this negative impact of CFL on our environment, LED technology has gradually become a green alternative to CFL in these recent few years.

There are several important specifications that must be taken into consideration in the development of the LED driver. These include low development cost, high energy efficiency, high power factor, galvanic isolation and long lifetime.

Low Development Cost: By having a low development cost of LED driver, the retail price of a developed LED lighting system can be greatly reduced, encouraging consumers to implement LED lighting system in general lighting application.

High Energy Efficiency: The efficiency of a LED lighting system can be improved by developing a highly energy-efficient LED driver. A highly-efficient LED lighting system will be capable of emitting the same amount of light with lesser power consumption, thus greatly reducing energy wastage in other forms of energy such as heat.

High Power Factor: Power factor (PF) represents how the energy is effectively transmitted from input to output, which is from an AC power source to LED in a LED lighting system. A high PF LED driver in a LED lighting system could help to utilize the energy generated by power station more efficiently (Hwang *et al*., 2012). In the near future, when a large amount of LED lightings are installed in building, a poor power factor LED system can deteriorate the power quality.

Galvanic Isolation: Galvanic isolation plays a vital role in isolating and protecting LEDs in LED lighting system. This specification is important to protect the LEDs from damaged due to short circuit or overcurrent in a lighting system.

Table 2: Category of the converters with and without electrical isolation.

Converter with electrical isolation	Converter without electrical isolation
Flyback converter	Buck converter
Forward converter	Boost converter
Push-pull converter	Buck-boost converter
Half Bridge converter	Cúk converter
Full-Bridge converter	-

Long Lifetime: Even though the LEDs can operate for a very long lifetime (around 100 000 hours), the lifetime of an overall LED lighting system is limited by the LED driver, which is around 45 000 hours (Wang *et al*., 2010; Wang *et al*., 2012; Chen and Hui, 2012; Ma *et al*., 2012). Hence, this limitation of designed LED driver in the market must be improved in future design and development of the LED drivers.

Street Lighting:

Currently, most of the existing street lighting system has implemented High-Intensity-Discharge (HID) lamps and magnetic ballasts in the lighting system (Hui *et al*., 2010). Magnetic ballasts are highly reliable with a lifetime of 20 years and it is recyclable. Alternatively, the lifetime for a HID lamp is around 24 000 - 60 000 hours only (GE Lighting, 2012). Based on these comparisons, LEDs become a great alternative in street lighting application as they offer longer lifetime than the HID lamps and magnetic ballasts. Thus, this further means that investing on LED lighting system will generate long-term return as one can save on the cost of maintenance for HID lamp replacement. LED driver for street lighting applications must possess several important specifications. These include high power factor, high energy efficiency, long product lifetime and recyclability (Arias *et al*., 2013; Hwu *et al*., 2011; Gacio *et al*., 2012, Hui *et al*., 2010, Long *et al*., 2009).

Liquid-Crystal-Display (LCD) Backlighting:

LCD is a flat panel display device which is used to present image, video or data for user. LCD has two different display categories, which are fixed image display and arbitrary image display. A fixed image display is capable of presenting image in either character or digit form only. This is because one of the LCD layer is built in with a 7-segment display or black colour pixel display in a box by box format. Alternatively, an arbitrary image display functions to present picture image or video. This type of display has smaller pixels than the fixed image display. Each of these pixels consists of red-green-blue (RBG) colour in order to generate more colours for presenting a colourful picture image. The arbitrary image display can be found in television, smart phone, digital picture frame, laptop and etc.

Current technology of LCD backlighting system called cold-cathode fluorescent lamp (CCFL) lighting system has been gradually replaced by LED lighting system as the LED technology offers the advantages of reducing the thickness and weight of LCD panel (Hsieh *et al*., 2011; Hsieh *et al*., 2012; Cho *et al*., 2011; Oh *et al*., 2009; Choi, 2013; Hsia and Kuo, 2010). An LED driver must possess several significant criterions for LCD backlighting applications. These include high luminance efficacy, high efficiency and accuracy in controlling dimming ratio and image quantity as well as low cost.

Traffic Control Light:

In recent years, LED technology has also become an alternative light source in traffic light system. Incandescent bulb does not last long and once then it is faulty can cause traffic hazards. The reliability of traffic light can be improved by replacing the incandescent-based traffic light with the LED-based traffic light. This is because most single LED light colour in a traffic light system composes of multiple LED strings with each LED string comprising of several LEDs connected in series. The important specifications that must be taken into account when designing a LED driver for traffic light system include long reliability, higher energy efficiency, high power factor, and low power consumption.

Vehicle Lighting System:

In vehicle lighting system, LED is applied in brake lights, left turn or right turn signal as well as in reverse lighting. For most of the latest vehicle models, LED is more commonly implemented in brake light system than left turn, right turn or reverse lighting system. This is because brake light is the most common and frequently used lighting signal which will light up to alert the car in the rear. LED, which offers longer lifetime and lower power consumption than incandescent bulb, has gradually replaced incandescent light bulb in vehicle lighting system as this technology can reduce the maintenance cost for brake light replacement while prolonging the lifetime of vehicle’s battery.

3.0 LED Driver Topologies:

Rectifier:

Rectifier topology is implemented in order to convert the AC power source into DC power source. A rectifier can be classified into two main different categories, which are uncontrolled rectifier (diode circuit), and controlled rectifier.

Uncontrolled rectifier is composed mainly of diodes. Power diode is most commonly used in rectifier circuit due to its simple to use, easily accessible and low cost characteristics. The main disadvantage of implementing an uncontrolled rectifier in the design of LED driver is that there is no control on the conduction time of the diode, and thus it is incapable of actively controlling the output DC voltage. However, all these disadvantages can easily be overcome by the implementation of controlled rectifier. A controlled rectifier is an active rectifier which can be used to obtain controlled output voltages while improving the efficiency of rectification. In controlled rectifier, actively controlled switches such as MOSFET and IGBT are used to replace power diode in order to control the rectification. Both MOSFET and IGBT have different power rating. MOSFET is more suitable for low voltage (<100V) application while IGBT is more suitable for high voltage application.

Switching Regulator:

The industrial requirements for power supplies are (Rashid, 1988),

- Isolation between the source and the load,
- High-power density for reduction in size and weight,
- Controlled direction of power flow,
- High conversion efficiency,
- Input and output waveforms with low total harmonic distortion, and
- Controlled power factor (PF) if the input power source is an ac voltage.

The regulated output voltage of a switching regulator is varied according to the ratio of duty cycle. Switching regulator can be classified into two main categories, which are with electrical isolation and without electrical isolation as shown in Table 2.

Flyback Converter:

In flyback converter, the secondary winding of the transformer functions as an inductor but not as a transformer. Hence, the output filter inductor can be eliminated. Moreover, it has universal input voltage range as the operation solely relies on the stored energy continuous conduction mode (CCM) or critical conduction mode (CrM). The typical operating power for flyback converter is below 100W.

Forward Converter:

The transformer of a forward converter does not store any energy. When there is no load, excess output voltage will be produced. Hence, in order to prevent this situation from happening, a large load resistance has been permanently connected across the output terminals. The typical operating power for forward converter is below 200 Watts.

Push-Pull Converter:

A push-pull converter creates less noise at the input line and it does not need an isolated power supply to drive the controlled switches. However, this converter has not been widely used due the flux walking phenomena. A push-pull converter is suitable for low-voltage applications.

Half-Bridge Converter:

In half-bridge converter, voltage across each of the controlled switches is only half of the input voltage in comparison with the forward converter. Thus the output power of a half-bridge converter is double that of the forward converter for the same semiconductor devices and magnetic core. The typical operating power of a half-bridge converter is in the range between 200W to 400W.

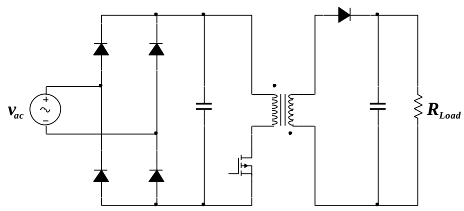

Fig. 1: A typical flyback converter circuit.

Full-Bridge Converter:

A full-bridge converter utilizes four power switches instead of two as in half-bridge converter. The maximum collector current for a full-bridge converter is only half of that of the half-bridge converter. Thus the output power of full-bridge converter is twice of that of a half-bridge converter with the same amount of input voltage and current. The typical power rating of a full-bridge converter is over 500 W.

4.0 Improvements on LED Drivers:

Power Factor:

According to the Energy Star power supply requirements for solid-state lighting luminaire, the power factor of a LED driver have to be at least 0.7 for residential applications and 0.9 for commercial applications. Consequently, a power factor correction (PFC) circuit is necessitated in the circuit design of a LED drive (Xie *et al*., 2012; Wang *et al*., 2010; Ma *et al*., 2012; Chang *et al*., 2012).

Topologies of integrated single-stage converter (Gacio *et al*., 2011; Alonso *et al*., 2008), flyback converter (Xie *et al*., 2012; Chen and Hui, 2012; Zhang *et al*., 2012; Hwu *et al*., 2011) and active power factor corrector circuit (Arias *et al*., 2013; Yan et. a;., 2012) have been implemented in order to achieve a near unity power factor. Single-stage topology has been developed instead of two-stage topology as it is much smaller in size, and cost-effective while capable of achieving high power factor and performing output current regulation. Besides, active PFC which utilizing active devices such as switching converter has been implemented in LED driver circuit instead of the passive PFC which utilizing passive components such as inductors and capacitors. This is because the size of the passive power factor corrector's components is large, and is not suitable for universal input voltage range applications.

Fig. 1 presents a typical two-stage conversion system using a line frequency rectifier and a flyback converter. The flyback converter is selected as the switching converter in the design of LED driver because the flyback converter provides galvanic isolation and its output voltage is easily regulated, while having fewer component counts, is compact in size and lower in cost (On Semiconductor).

As discussed earlier, there are three operating modes for a flyback converter, which are DCM, CCM and CrM. The flyback converter with CCM and PFC features are commonly implemented in high power load applications. Although this mode of operation has minimum power losses due to lower RMS current required, it is unsuited for applications necessitating universal input voltage range as it suffers high voltage stress at high input voltage and light loads (Deng *et al*., 2004).

For CrM and DCM PFC converters, the output powers of these converters are dependent on the duty cycle of the controlled switch. Therefore, these two modes of operation are preferred than CCM in the design of LED driver. For low power application, PFC operating under CrM tends to have a relatively high switching frequency. Conversely, for high power application, PFC operating under DCM tends to have high peak currents. Based on these comparisons, DCM mode of operation is considered more suitable and thus has been chosen in optimum design of low power LED driver.

DCM mode of operation is capable of achieving high power factor for a LED driver. This is proven by the following formula which has been derived as (On Semiconductor),

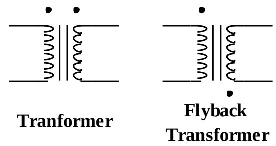

Fig. 2: Schematic drawing of ideal transformer and flyback transformer.

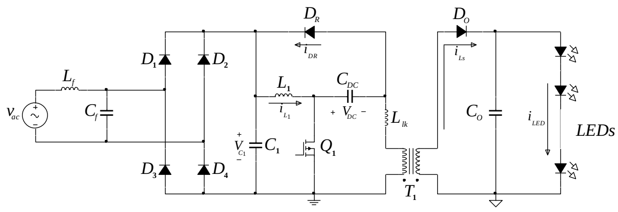

Fig. 3: Basic circuit configuration of leakage inductance energy recycling circuit.

$$I_{in}(t) = \frac{v_{in}(t)}{2L}\left(\frac{t_{on}t_{cycle}}{T_{sw}}\right). \quad (1)$$

From equation (1), it can be concluded that by keeping $t_{on}t_{cycle}/T_{sw}$ constant, a sinusoidal line current can be obtained as the input current is proportional to the input voltage, which thus leads to a unity power factor as there is no phase shift between the input voltage and input current.

Efficiency:

From the schematic drawing as shown in Fig. 2, a normal transformer and a flyback transformer are quite physically identical. However, this is not true as there are many features or properties which are different in between them. For example, in contrast to a general transformer, a flyback transformer is operated as an inductor that functions to store, and couple energy as well as provide input-to-output isolation. Besides that, the operation of a flyback transformer is such that when the primary side of the flyback transformer is conducting, the primary side will start to store energy. Once the flyback transformer is no longer conducting, the stored energy will be released to the secondary side. This is utterly different with the general transformer where the current flows concurrently in both the primary and secondary side.

Conventionally, the efficiency of a single-stage flyback converter is typically not high, which is around 80% only. Technically speaking, a flyback transformer plays a paramount important role in determining the performance of a flyback converter. Therefore, it is not inappropriate to conclude that one of main root cause for this low efficiency is due to the leakage inductance of the transformer. This is because each isolated flyback transformer possesses leakage inductance around the coil winding, which is around 5% of the magnetizing primary inductance (Arsenov, 2013) .Aproposed method of improving the efficiency of a LED driver that is by recycling the leakage inductance energyvia a freewheeling diode and then stored in an input capacitor. This proposed method has successfully improved the efficiency of the LED driver, which is from 80% to 90%.

Fig.3.presents the proposed schematic diagram where Q_1 is a power switch, D_R is a freewheeling diode, and C_1 is an input capacitor. Some of the energy is stored as leakage inductance L_{LK} of the flyback transformer is not ideal. The operation of the proposed method is such that when Q_1 is switched off, current of L_{LK} flows through D_R, and the L_{LK} energy is then stored in C_1. The total amount of time, $t_{recycle}$ that is necessary for this recycling process to be completed can be described as,

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$$t_{\text{recycle}} = \frac{T_r}{4} = \frac{\pi\sqrt{L_{LK}C_1}}{2}. \quad (2)$$

The equation has been derived, where T_r is the resonant period. Besides, it is of no doubt that the off time of switch Q_1 must be greater than $t_{recycle}$ in order to assure that leakage inductance energy is completely recycled.

The proposed recycling method is capable of reducing the voltage spike and ringing on switch Q_1. Besides that, implementation of capacitor C_1 in the circuit is also able to effectively improve the electromagnetic interference (EMI), which allows reduction in the capacitance value of C_f and inductance value of L_f. Both C_f and L_f function as an EMI filter which is utilized in isolating high-frequency current harmonics at input.

Harmonic Reduction:

In the process of converting AC power sources into DC power sources, the electronics loads (electronics component used in the power supplies of LED driver) will generate current harmonic distortion at the AC power supplies side. The unwanted harmonic is one of the factors that lead to higher amount of current flowing out from the power supply, which causes higher temperature induced in neutral conductors and distribution transformers.

In order to reduce the harmonics generated to the power supply by LED driver, there are a few techniques that have been discovered, which is harmonic injection method and an average current-mode control method (Athab, 2006; Wang *et al*., 2011). Harmonic injection method is introduced as one of the method for improving the performance of the DCM boost converter. With the injection of harmonic signals into the measured voltage output, the duty cycle of the switch will be modified. As a result, the total harmonic distortions

Will be reduced. Average current mode control is an alternative method that can be implemented for reducing the current harmonics as it can synthesize a suitable low-harmonics sinusoidal waveform for low input current.

Dimming Capability:

The indoor lighting with dimmable features where brightness of the LED lamp can be adjusted based on human needs while bringing adequate light level in different types of room as well as saving energy consumption has yield several benefits for consumer. Dimming method can be categorized into two major different types: PWM dimming method and TRIAC dimming method.

PWM dimming method can be subdivided into three basic ways such as PWM-enabled dimming, PWM series dimming, and PWM shunt dimming. The PWM enable dimming operates the converter to keep it turn on and off by means of enabling or disabling input at high frequency to dim the lamp light. The PWM series dimming is applied a series switch for interrupt action. This means that the load is switched on and off with the controlled PWM signal while maintaining the output voltage at constant value. Finally, the PWM shunt dimming uses a switch that is connected across the LED loads in order to divert the lamp current by the dimming signal. Based on the PWM dimming techniques described above, PWM enable dimming method and PWM shunt dimming method are appropriate choices to be applied in LED driver for indoor lighting application (Gacio *et al*., 2011; Gacio *et al*., 2012; Sarhan and Richardson, 2013; Sarhan, 2008).

Lifespan:

The lifespan of a LED driver is closely related to the electronic components used to construct the driver. One of the most commonly used electronic components in LED driver is electrolytic capacitor. In comparison with non-electrolytic capacitor, it has a much wider range of capacitance value with different voltage rating. Therefore, it is widely adopted in LED driver power converter circuit. However, electrolytic capacitor is only capable of operating for several thousand hours only. In other words, it will be the first component that becomes faulty than any other components in a LED driver system. The low lifespan electrolytic capacitor causes the performance of power driver to drop instantly while reducing the lifespan of LED lighting system due to the unregulated output power. Hence, from literatures reported in (Wang *et al*., 2010; Wang *et al*., 2012; Chen and Hui, 2012; Ma *et al*., 2012), the electrolytic capacitor has been replaced by polyester film or ceramic capacitors in order to achieve longer lifetime of power driver. Table 3 presents the comparison on the properties of three types of capacitors, which include electrolytic, polyester film and ceramic capacitor (Qin *et al*., 2008).

LED can be operated with a pulsating current (Broeck *et al*., 2007, Spiazzi *et al*., 2005). An electrolytic capacitor-less LED driver has been employed to convert AC voltage to a pulsating direct current with twice the line frequency in order to drive the LEDs. Fig. 4 presents the schematic diagram of the capacitor-less driver, where C_0 is the storage capacitor, and L_0 is a small value low-pass inductor connected in series with the LED strings (Wang *et al*., 2010). In this circuit, C_0 is used to filter only the High-frequency harmonic current. Consequently, a film or ceramic capacitor can be used in the circuit, replacing the electrolytic capacitor as the output capacitance of the circuit is very small. As a result, the lifespan of the LED driver can be extended.

Table 3: Comparison among several types of capacitors (Sarhan, 2008).

Capacitor	Lifetime (hours)	Available range	Maximum capacitance per unit volume (μF/cm^3)
Electrolytic	< 10000	1 μF – 12 mF	200
Polyester Film	>10000	10 pF – 80 μF	30
Ceramic	>10000	10 pF – 10 μF	5

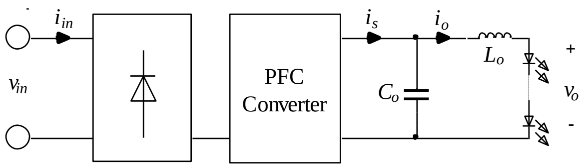

Fig. 4: Schematic diagram of PFC converter.

On the other hand, a propose method in prolonging the lifespan of the driver that is reducing the crest factor of the output current (Wang *et al*., 2010). Crest factor of an output current can be defined as the ratio of the peak to RMS value of output current. In other words, the higher the crest factor, the higher the peak current and average driving current. A high crest factor is undesirable in the design of LED driver due to the fact that the maximum tolerable current of a LED decreases as the operating temperature of the power driver increases (Buso *et al*., 2008). The crest factor of the output current is two when the input power factor is unity. In order to decrease the crest factor, a 3rd and 5th harmonics have been injected into the input current. This method has allowed the crest factor to be reduced to value of 1.34 while maintaining the input power factor at value of 0.90.

Latest Trends and future developments:

In LED lighting power conversion system, both single-stage and multiple-stage power converter circuits can be implemented in order to improve the input power quality of a system. Two-stage or multiple-stage power converter circuit is needed in high voltage applications, for instance in street lighting. On the other hand, for low voltage applications such as indoor lighting, single-stage or two-stage power converter circuit will be of sufficient. In order to design a LED driver which can be utilized for industry and home applications, the specifications of LED driver must be closely matched with the design requirements for industry area which have been mentioned in section V.

Most of the LED lighting applications are implementing uncontrolled rectifier in converting AC sine wave into full wave, where the waveform is then filtered by bulk capacitor in order to obtain a smooth DC waveform. Besides, in order to improve the input power factor, a power factor correction (PFC) circuit and a flyback converter operating under DCM is employed. However, a two-stage converter topology is required, which will increase cost slightly. However, a controlled rectifier can be considered for transforming AC power into DC power to reduce the task of the single-stage flyback converter.

Conclusion:

A comprehensive review on the development of LED driver including the latest topologies for indoor lighting applications has been presented in this paper. A detail study of the latest topology has been described, which can be a useful guide when designing a LED driver to meet the requirements of high power factor, high efficiency, dimmable and low harmonics distortion at the AC side.

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