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# Improved power quality based high brightness LED lamp driver

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**Abstract**

This paper deals with a power factor corrected (PFC) improved power quality based LED lamp driver. The proposed driver consists of a PFC Cuk DC-DC converter which operates in continuous conduction mode (CCM) to improve the power quality at input AC mains. The design, modeling and simulation of an 18W LED (six 3W LEDs in series) driver are carried out in MATLAB/SIMULINK environment for a 220V, 50 Hz AC mains with constant load voltage of 72V. Each LED has a forward voltage of 12V and a forward current of 0.25A. The power quality indices such as total harmonic distortion of AC mains current ($THD_i$), power factor (PF), distortion factor (DF), displacement power factor (DPF) and crest factor (CF) are calculated to study the behavior of proposed LED lamp driver.

*Keywords:* Continuous Conduction Mode (CCM), Cuk DC-DC Converter, Diode Bridge Rectifier (DBR), LED Lamp Driver, Power factor Correction (PFC).

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## 1. Introduction

Across the world approximately 25% of the total electrical energy is consumed by artificial light sources. With the advancement of lighting technology in past few years, high luminance light emitting diodes (LEDs) are investigated as a source of artificial light because of their many advantages like high luminous efficacy, long life, environment friendly due to less mercury contents, easily dimmable, low maintenance, flicker less start, robust in structure and least affected by vibrations. LED lighting system mostly consists of two parts: LED driver and LED module. Today power LEDs are available in different power ratings of 1W, 3W and 5W with different forward voltage and current ratings. New power LEDs are designed for nominal currents of 250mA onwards and forward voltage in the range of 3-12V. Currently power LEDs are available at higher cost, but their long life makes them economical to use (Huang *et al*, 2008; Huang *et al*, 2011).

Since LEDs are special types of diodes, the default method for driving them is controlling the DC forward current through the resistor, but this kind of approach is considered as less efficient to glow the LED lamp due to excessive power loss in the resistor. If the primary source of energy is the AC mains, then some kind of AC-DC converter must be placed between the line and the high brightness (HB) LEDs. But as per international standard IEC 61000-3-2 for Class C equipments (International Electro technical Commission standards for lighting) harmonic contents of the line current must be within the specified limits. Therefore, the best method is to use power factor corrected (PFC) AC-DC converters, which are known as power factor pre-regulators (PFP). The commonly used PFP are buck, buck-boost, Cuk, Sepic, Zeta in non-isolated and flyback converter families in isolated mode. These can operate in continuous conduction mode (CCM) or dis-continuous conduction mode (DCM) to achieve better power quality at input AC mains (Aguilar and Henze 2010). In CCM, a perfect sinusoidal input current with almost unity power factor can be obtained with the help of one outer voltage feedback loop and one inner current feedback loop.

LED driver consists of a diode bridge rectifier (DBR) and a resistor which provides a constant current to avoid the damage of LEDs. Such circuits introduce power quality issues like poor power factor and higher harmonic contents in the AC mains current as well as poor efficiency since only 20-30% of input power in converted into light. To comply with IEC-61000-3-2 class C equipments, a PFC stage is required between DBR and the LED module to improve the power quality at AC mains (Huang *et al* 2010; Garcia *et al* 2010; Myunghyo Ryu *et al* 2011 and Chun *et al* 2011).

In this paper, a power factor corrected (PFC) AC-DC Cuk converter operating in CCM (Continuous Conduction Mode) is proposed for LED driver. In solid state LED driver, power factor corrected (PFC) AC-DC converter improves the input power factor and reduces total harmonic distortion of AC mains current ($THD_i$) and also maintains constant lamp voltage for the stable operation of LED lamp. Since PFC converter is operated at high switching frequency of 60 kHz, it reduces the size and weight of passive components like inductor and capacitor.

## 2. Proposed Topology of LED Driver

The circuit diagram of proposed LED driver is shown in Figure 1 which consists of a DBR and PFC Cuk AC-DC converter connected in cascade configuration. The outer voltage feedback controller senses the DC voltage and compared it with the reference voltage to generate the error voltage, which is passed through the Proportional Integral (PI) voltage controller to generate the reference current. Thereafter this reference current is compared with the sensed current to generate the PWM pulses, to maintain proper illumination of LED modules. In proposed LED driver as shown in Figure 1, a Cuk buck boost AC-DC converter is selected as the PFC converter to drive the lamp. The power switch M is operating at 60 kHz frequency.

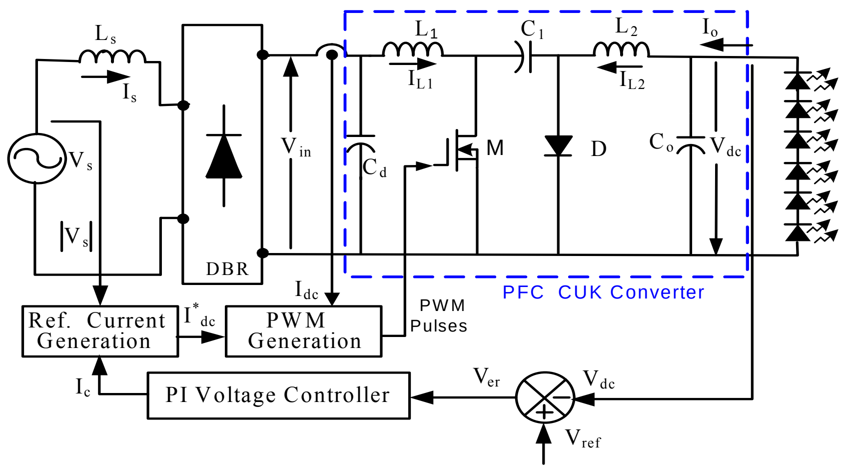


**Figure 1.** Proposed PFC Cuk converter based LED driver

## 3. Design and Analysis of Proposed LED Driver

The following considerations are made to analyze the proposed topology of LED driver.

- All the components of LED driver are considered ideal.
- During steady state LED behaves as a pure resistor.
- DC link voltage must be selected properly to minimize component stress and to confirm CCM operation.

The design procedure includes calculations of the components of PFC based Cuk AC-DC converter is as follows.

*3.1 Design of Components of Cuk Converter:*

The value of duty cycle, for a Cuk converter operating in continuous conduction mode (CCM) (De Britto *et al* 2008; Ali *et al* 2010) is defined as,

$$D = \frac{V_{dc}}{V_s + V_{dc}} \tag{1}$$

The value of inductance ($L_1$) is determined by allowing the peak-to-peak ripple current $\Delta I_{L1}$. The value of inductance ($L_1$) can be given (De Britto *et al* 2008) as,

$$L_1 = \frac{V_s(1\text{-}D)}{\Delta I_{L1} f_s} \tag{2}$$

The value of inductance ($L_2$) is determined by allowing the peak-to-peak ripple current $\Delta I_{L2}$. The value of inductance ($L_2$) can be defined (De Britto *et al* 2008) as,

$$L_2 = \frac{V_{dc}(1\text{-}D)}{\Delta I_{L2} f_s} \tag{3}$$

The coupling capacitor ($C_1$) is designed on the basis of its ripple voltage content. The maximum voltage handled by the coupling capacitor is equal to the peak value of the input voltage. The design of capacitor $C_1$ is very important because the current through it changing its direction very frequently. It can be defined as (De Britto *et al* 2008),

$$C_1 = \frac{V_{dc} D}{R_{lamp} f_s \Delta V_{c1}} \tag{4}$$

The DC link capacitor ($C_o$) must have sufficient capacitance to maintain constant DC link voltage with negligible ripple content and must have to provide continuous load current at high switching frequency. It can be estimated as,

$$C_o \geq \frac{V_{dc}(1\text{-}D)}{R_{lamp} f_s \Delta V_{co}} \tag{5}$$

where, D is duty cycle, $V_{dc}$ is DC link voltage, $V_s$ is the value of AC mains rms voltage, $I_o$ is average output current, $f_s$ is switching frequency of the active switch, $R_{lamp}$ is the LED lamp resistance under steady state, $\Delta V_{c1}$ is the ripple voltage of coupling capacitor, $\Delta V_{co}$ is the ripple voltage of DC link capacitor.

The calculated minimum and maximum duty cycle are 0.21 and 0.29. For a switching frequency of 60 kHz and DC link voltage of 72 V, the calculated values of inductors, $L_1$=23.70mH for a ripple current of $\Delta I_{L1}$= 0.15A (60% of average output current) (selected as 20mH) and $L_2$=18.96mH for a ripple current of $\Delta I_{L2}$= 0.05A (20% of average output current) (selected as 20mH). The calculated value of coupling capacitor $C_1$=0.1μF (for a voltage ripple of 2%) and the calculated value of DC link capacitor is $C_o$=22.85μF (for a voltage ripple of 0.2%).

## 4. Control Scheme

Under normal operating condition, a single-phase AC supply system can be modeled as a sinusoidal voltage source of amplitude $V_{sm}$ and frequency f. The instantaneous input voltage is given as,

$$V_s = V_{sm} \sin\omega t \tag{6}$$

From input supply voltage, a voltage template u (t) is evaluated to generate reference current and controls the AC mains current to follow the reference current to achieve high power factor using a PFC Cuk converter. This control scheme consists of a PI (Proportional Integral) voltage controller, reference current generation and finally the PWM generation, which provides switching pulses to the solid state power switch.

A PI voltage controller is selected for the voltage loop for regulation of the output voltage. The DC voltage, $V_{dc}$ is sensed and then compared with set reference voltage $V_{dc}^*$. The resulting voltage error $V_e$(n) at $n^{th}$ sampling instant is given as,

$$V_e(n) = V_{dc}^*(n) - V_{dc}(n) \tag{7}$$

and the output of PI voltage regulator at $n^{th}$ sampling instant can be given as,

$$I_c(n) = I_c(n\text{-}1) + K_p\ \{V_e(n) - V_e(n\text{-}1)\} + K_i V_e(n) \tag{8}$$

where, $K_p$ and $K_i$ are the proportional and integral gains.

Current regulation loop is required for active wave-shaping of input AC current to achieve unity power factor and reduce current harmonics. Current signal must match the rectified line voltage as closely as possible to improve the input power factor. The input voltage template u(t) obtained from sensed supply voltage is multiplied with its amplitude (the output of PI voltage regulator) and the resulting signal forms the reference for input current.

$$I_{dc}^* = I_c(n) * u(t), \text{ where, } u(t) = |V_{sm}| / V_{sm} \tag{9}$$

The inductor current error is the difference of reference current and sensed inductor current. This error signal is amplified by a gain $K_c$ and compared to fixed frequency carrier wave to generate PWM gating signals for power MOSFET of the PFC Cuk converter.

$$\Delta I_{dc} = I_{dc}^* - I_{dc} \tag{10}$$

If $K_c * \Delta I_{dc} >$ carrier signal then M = 1 else M = 0.

This gating signal (M) is given to the MOSFET of Cuk converter.

## 5. Matlab Model of Proposed LED Driver

The model of the proposed PFC based Cuk converter for LED driver is developed in MATLAB/SIMULINK and it is shown in Figure 2 in which LED lamp is considered as a resistor at high frequency under the steady state condition.

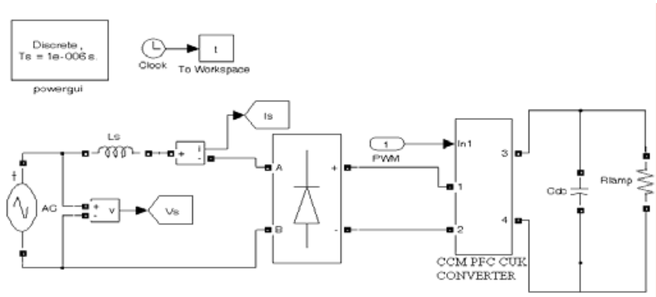


**Figure 2.** MATLAB Model of Proposed LED driver

The PFC Cuk converter based topology is modeled using Proportional Integral (PI) controller with the current multiplier approach for operating it in continuous condition mode (CCM). The switching frequency is maintained constant at 60 kHz for PWM generation. The designed values of the Cuk converter components obtained from equations (1)-(5) are selected appropriately to achieve desired power quality at input AC mains. These component values along with PI controller gain parameters are provided in Appendix.

## 6. Results and Discussion

The main objective of the modeling and simulation is to validate the design of proposed PFC based LED driver which has low THD of AC mains current and low crest factor for the wide input voltage applications. The DC link voltage is kept almost constant at 72 V using closed loop control, thus the lamp current is maintained constant throughout the wide input voltage range (170V-270V), which realizes the constant lamp power. Figure 3 shows the input AC mains voltage ($V_s$) and current ($I_s$) waveforms, inductor current ($I_{L1}$), mean DC link voltage ($V_{dc}$), LED lamp voltage ($V_{lamp}$) and lamp current ($I_{lamp}$) at 170 V under steady state conditions. The input mains current ($I_s$) is closed to sinusoidal and in phase with input AC mains voltage which ensures the high power factor operation of the proposed circuit. The inductor current ($I_{L1}$) confirms the CCM (Continuous Conduction Mode) operation of the circuit, since the inductor current never reaches to the zero value in one switching cycle. Moreover, the lamp voltage and current are close to the rated value at AC mains voltage of 170V.

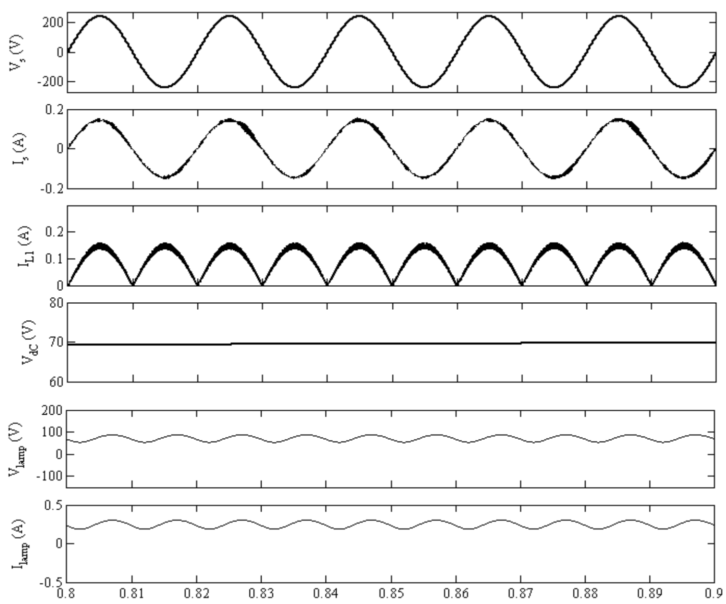


**Figure 3.** Steady state performance of PFC LED driver in terms of source voltage ($V_s$), source current ($I_s$), inductor current ($I_{L1}$), mean DC link voltage ($V_{dc}$), lamp voltage ($V_{lamp}$) and lamp current ($I_{lamp}$) at 170V

Figure 4 shows the input AC mains voltage ($V_s$) and current ($I_s$) waveforms, inductor current ($I_{L1}$), DC link voltage ($V_{dc}$), LED lamp voltage and lamp current at 220 V AC mains voltage under steady state conditions. The input mains current is following the input main voltage in phase, thus high input power factor is achieved at rated voltage of 220V. The inductor current ensures the CCM operation of the proposed LED driver. The lamp voltage and current remains constant and close to the rated value.

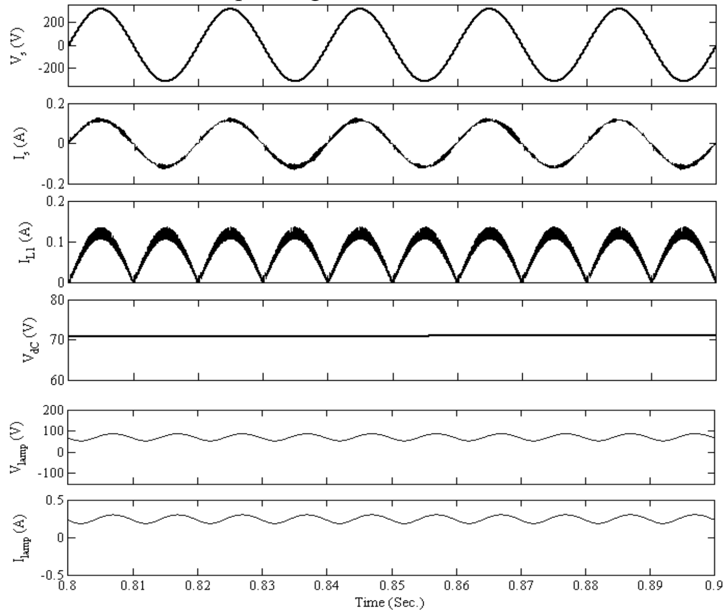


**Figure 4.** Steady state performance of PFC LED driver in terms of source voltage ($V_s$), source current ($I_s$), inductor current ($I_{L1}$), mean DC link voltage ($V_{dc}$), lamp voltage ($V_{lamp}$) and lamp current ($I_{lamp}$) at 220V

Figure 5 shows the input AC mains voltage ($V_s$) and current ($I_s$) waveforms, inductor current ($I_{L1}$), DC link voltage ($V_{dc}$), LED lamp voltage and lamp current at 270 V AC mains voltage under steady state condition. The input AC mains current still maintains its shape close to sinusoidal, hence high input power factor is confirmed at a voltage of 270V. The inductor current makes sure that the proposed circuit is working in CCM. The lamp voltage and current confirms the constant power operation of the proposed LED driver.

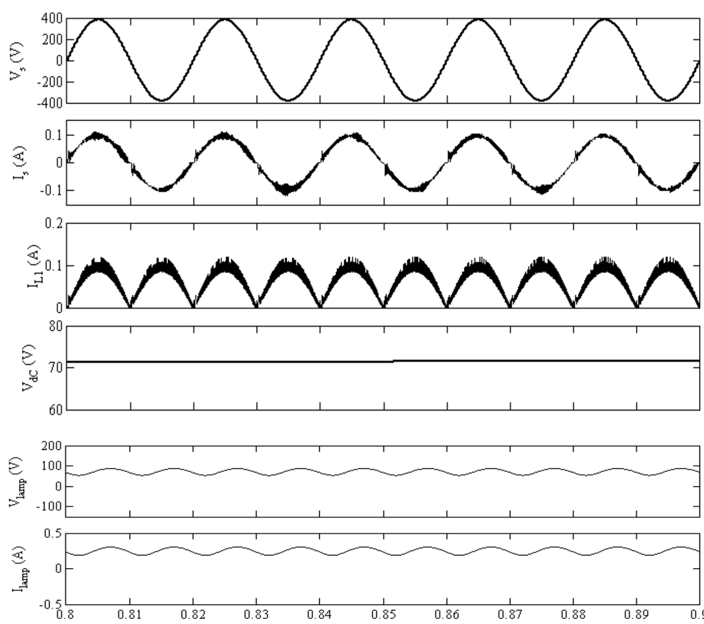


**Figure 5.** Steady state performance of PFC LED driver in terms of source voltage ($V_s$), source current ($I_s$), inductor current ($I_{L1}$), mean DC link voltage ($V_{dc}$), lamp voltage ($V_{lamp}$) and lamp current ($I_{lamp}$) at 270V

The input current waveforms along with its harmonic spectra and THD have been shown in Figure 6, Figure 7 and Figure 8 at AC mains voltage of 170 V, 220V and 270V respectively. The input mains current is sinusoidal throughout, thus high power factor is achieved for a wide variations of AC mains voltage. The input current THD is well within the IEC-61000-3-2 for the proposed LED driver.

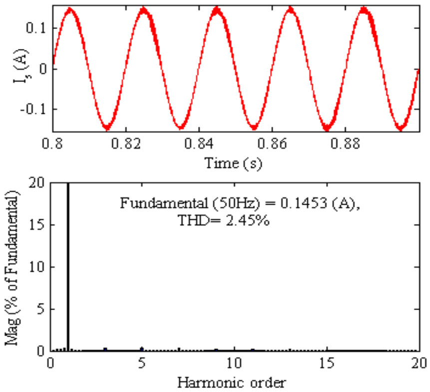


**Figure 6.** Input current waveform and its harmonic spectra at input AC mains voltage of 170V

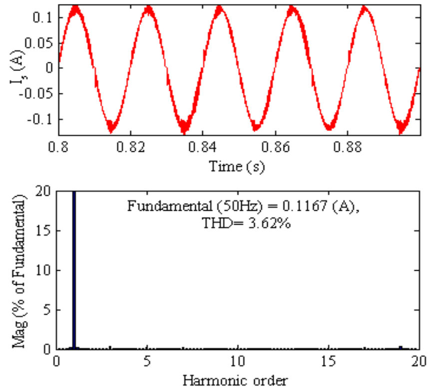


**Figure 7.** Input current waveform and its harmonic spectra at input AC mains voltage of 220V

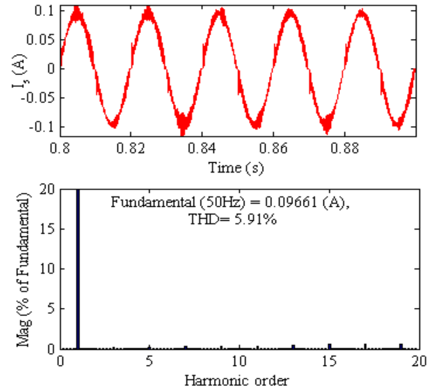


**Figure 8.** Input current waveform and its harmonic spectra at input AC mains voltage of 270V

It has been observed from these results that the THD of AC mains current is between 1.95-6% for the wide range of AC mains voltage from 170V-270V.

The power quality indices of the proposed PFC Cuk converter for LED driver are listed in Table 1. The DC link voltage, lamp voltage and lamp current have maintained almost constant for wide AC mains voltage variations i.e. from 170V-270V. Table 1 also shows the variations of power factor, displacement power factor, distortion factor, crest factor and % THD of AC mains current of proposed LED driver with the variation in input AC mains voltage. The power quality indices of the proposed LED driver are within the norms of international standard IEC 61000-3-2 for class C equipments (International Electro technical Commission standards for lighting). The input power is close to the rated value of the lamp power in the proposed LED driver.

**Table 1.** Performance Indices of Proposed LED Driver

| $V_s$ (V) | $I_s$ (A) | $P_s$ (W) | $V_{lamp}$ (V) | $I_{lamp}$ (A) | PF | DPF | DF | % $THD_i$ | CF |
|---|---|---|---|---|---|---|---|---|---|
| 170 | 0.1035 | 17.56 | 70.73 | 0.2456 | 0.9985 | 0.9997 | 0.9987 | 2.45 | 1.379 |
| 180 | 0.0987 | 17.74 | 71.10 | 0.2469 | 0.9990 | 0.9996 | 0.9993 | 2.10 | 1.406 |
| 190 | 0.0942 | 17.87 | 71.38 | 0.2478 | 0.9987 | 0.9995 | 0.9991 | 1.95 | 1.407 |
| 200 | 0.0902 | 18.01 | 71.64 | 0.2488 | 0.9987 | 0.9994 | 0.9992 | 2.27 | 1.406 |
| 210 | 0.0863 | 18.09 | 71.81 | 0.2493 | 0.9985 | 0.9992 | 0.9992 | 2.34 | 1.409 |
| 220 | 0.0829 | 18.19 | 72.00 | 0.2500 | 0.9974 | 0.9991 | 0.9982 | 3.62 | 1.401 |
| 230 | 0.0797 | 18.25 | 72.12 | 0.2504 | 0.9959 | 0.9989 | 0.9969 | 3.82 | 1.406 |
| 240 | 0.0782 | 18.70 | 72.24 | 0.2508 | 0.9964 | 0.9986 | 0.9977 | 4.01 | 1.378 |
| 250 | 0.0737 | 18.35 | 72.32 | 0.2511 | 0.9961 | 0.9984 | 0.9976 | 4.49 | 1.408 |
| 260 | 0.0711 | 18.40 | 72.40 | 0.2514 | 0.9957 | 0.9980 | 0.9976 | 5.47 | 1.407 |
| 270 | 0.0686 | 18.42 | 72.48 | 0.2517 | 0.9948 | 0.9978 | 0.9969 | 5.91 | 1.408 |

## 7. Conclusions

A PFC Cuk buck-boost AC-DC converter based LED driver has been proposed with improved power quality for wide range of AC mains voltage. The proposed LED driver with PFC Cuk converter has shown high level of performance such as unity power factor and crest factor of nearly 1.4 for the wide range of AC mains voltage. The current harmonics of the proposed LED driver have been compared with the current harmonic limits of IEC 61000-3-2 Class-C equipments and these have been found within the norms. The DC link voltage has been maintained constant, which realizes the constant lamp power irrespective of the change in AC mains voltage. The proposed driver has THD of AC mains current under 6% for the AC mains voltage range of 170V-270V.

## Appendix

Rated lamp power: 18W, rated lamp current: 0.25 A, rated lamp voltage: 72 V, switching frequency of PFC switch ($f_s$): 60 kHz, PI controller gains ($K_p$): 0.0055, ($K_i$): 0.025, PFC components: - inductor ($L_1$): 20 mH, inductor ($L_2$): 20 mH, coupling capacitor ($C_1$): 0.1 μF, DC link capacitor ($C_o$): 22 μF.

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**Biographical notes**

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