An Interleaved Single Stage LED Driver with Coupled Inductors and LC Resonant Converter

Mrutunjayya[1] Ms. K. Nethra[2]
[1]M.Tech Student [2]Assistant Professor
[2]Department of Electronics and Electrical Engineering
[1,2]Reva Institute of Technology and Management Bangalore, Karnataka, India

Abstract— This paper proposes an interleaved single-stage LED driver with coupled inductors and LC resonant converter. The papers presents LED driver with coupled inductors and series-resonant converter into a single stage power conversion circuit. In this paper an interleaved boost converter is used for power factor correction and resonant circuit for zero voltage switching in order to reduce switching losses. Since soft-switching is used to reduce switching losses, it is required to operate interleaved boost converter in discontinuous conduction mode. Analysis of operational modes and design equations are described and simulation is carried out in MATLAB to understand the operation. Closed loop simulation is also carried out. Finally, a prototype 165W rated LED driver is developed and tested with 110V input voltage.

Key words: LED Driver, soft- switching, coupled inductors, LC resonant converter

I. INTRODUCTION

Incandescent bulbs which are used as source for lighting has poor lighting efficiency and have very less life span where as light emitting diode has long life, mercury free and has conversion efficiency more by 70% compared to conventional street lighting [1]-[3]. The study and implementation of a high frequency pulse LED driver with self-oscillating circuit is presented. The self-oscillating half-bridge series resonant inverter is adopted in this LED driver and the circuit characteristics of LED with high frequency pulse driving voltage is also discussed [4].

An efficient driver circuit is proposed in for light-emitting-diode (LED) lamps with a dimming feature. The driver consists of a flyback converter in series with the dc-link [5]. The efficient drivers for power factor correction o input side is done using input filter and the converters like boost, buck-boost, flyback etc, and zero voltage switching is done by using LLC resonant circuit where voltage goes to zero before the switch turns on [5]-[11].

Street lighting provides safe environments for vehicle riders. The traditional street lighting system has been mercury lamps with low cost and low efficiency. But present street lighting system with LED has high efficiency and long life [11]-[3].

The conventional two-stage LED driver with LLC resonant converter powering 70W lamp is shown in fig. 1. It consists of LC input filter (Lf and Cf) connected with a full-bridge rectifier(D1, D2, D3 and D4), an interleaved boost PFC converter(including two capacitors Cin1 and Cin2, two diodes D_B1 and D_B2, two inductors L1 and L2, two power switches S1 and S2,a DC-linked capacitor CB), and a half-bridge-type LLC resonant converter (including a DC-linked capacitor C_B, two power switches S3 and S4, a resonant capacitor Cr, a resonant inductor Lr, a center-tapped transformer T1 with two output windings, two output diodes D5 and D6 and an output capacitor Co) along with an LED [13]. Since the system consists of two stages, this effects the efficiency of the system and the components and switches required are more in such LED driver.

In order to overcome these challenges, this paper proposes an interleaved single stage LED driver with coupled inductors and LC resonant converter, suitable for street lighting applications. Design equations and analysis of operational modes are presented in the proposed topology and closed loop simulation is carried out to regulate output voltage.

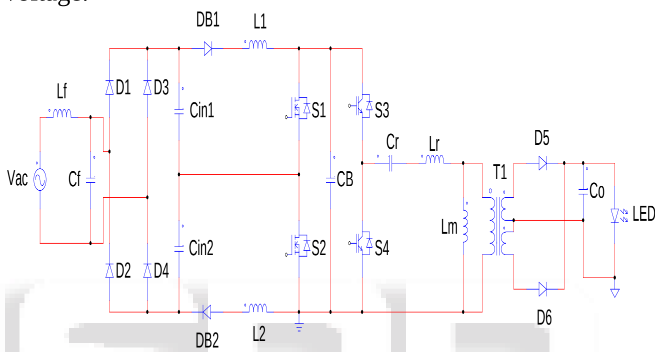

Fig. 1: The conventional two-stage LED driver for street-lighting applications

II. ANALYSIS OF OPERATIONAL MODES OF PROPOSED LED DRIVER

Fig. 2 shows the presented led driver with input filter followed by full bridge rectifier , interleaved boost converter and LC resonant converter with full brigdge rectifier for power conversion. The circuit has two capacitors at input side (Cin1 and Cin2) and the interleaved boost converter consists of two coupled inductors (LB11,LB12 and LB21,LB22), two diodes (D_B1 and D_B2) two switches (S1 and S2), and DC-bus capacitor (C_DC). The two switches (S1 and S2) and DC-bus capacitance (C_DC) is shared by interleaved boost converter and series resonant converter, apart from this resonant converter has a resonant inductor (Lr) and a resonant capacitor (Cr) and a series full bridge rectifier having four diodes (Do1,Do2,Do3 and Do4), and a capacitor Co along with LED as load

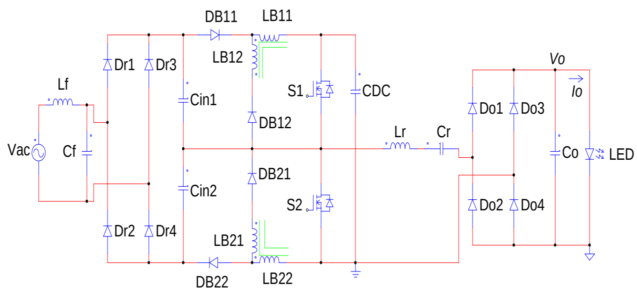

Fig. 2: The proposed single-stage LED driver with coupled inductors and LC resonant converter

Fig. 3 presents the simplified circuit of the proposed single-stage LED driver, obtained while analyzing the operational modes. Following assumptions are taken care of, in order to analyze the operational modes.

(a) Since switching frequencies of two switches *S1* and *S2* are much higher than that of utility-line voltage V_{AC}, the sinusoidal utility-line voltage can be considered as a constant value for each high-frequency switching period.

(b) V_{REC1} and V_{REC2}, respectively, represent the rectified input voltage sources on the capacitors *Cin1* and *Cin2*.

(c) Power switches are operated at 180 degree phase shift, and their anti-parallel diodes and drain-source capacitors (C_{DS1} and C_{DS2}) are considered.

(d) The voltage drops of diodes D_{B11}, D_{B12}, D_{B21}, D_{B22}, *Do1, Do2, Do3* and *Do4* are neglected.

(e) Coupled inductors (including L_{B11} and L_{B12}; L_{B21} and L_{B22}) are designed to be operated in DCM for naturally achieving PFC.

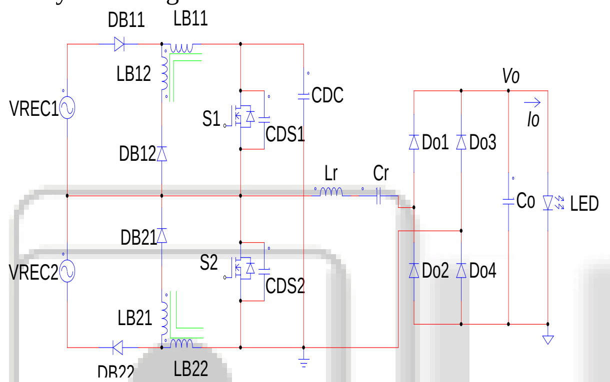

Fig. 3: Simplified circuit of the proposed single-stage LED driver

III. Analysis of Modes

Mode 1 (to≤t<t1; in Fig. 4(a)): At to the diode of the switch and diode D_{B21} are forward biased. The resonant capacitor Cr charges the resonant inductor Lr through C_{DS2}, Do2, Do3, Co and LED. The coupled inductors LB21 and LB22 provide energy to C_{DS2} through D_{B21}. S1 turns on with zero voltage switching as drain to source voltage of S1 is zero at time t1.

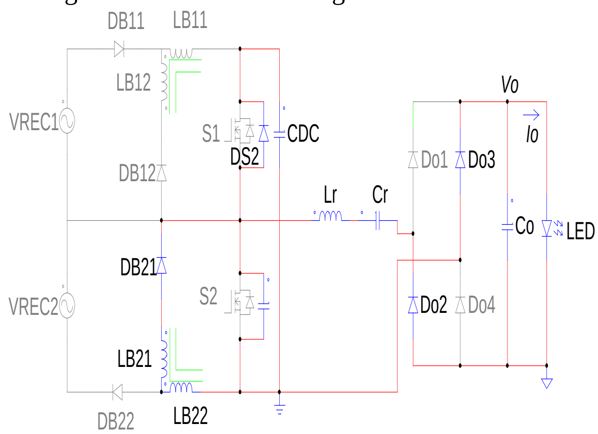

Fig. 4(a): Equivalent circuit for mode 1

Mode 2 (t1≤t<t2; in Fig. 4(b)): In this mode the V_{REC1} provides energy to coupled inductor L_{B11} through switch S1. The inductor current i_{LB11} increases linearly from zero, it can be expressed as

$$i_{LB11} = \frac{|\sqrt{2}v_{AC-rms}\sin(2\pi f_{AC}t)|}{2L_{B11}}(t - t_1), \qquad (1)$$

where v_{AC-rms} is rms value of input line voltage, and f_{ac} is the utility-frequency frequency.

The DC-bus capacitance C_{DC} and the resonant inductor Lr provide energy to capacitors C_{DS2}, Cr, and Co and to the LED through diodes Do1 and Do4. Capacitor C_{DS2} is energized by coupled inductors L_{B21} and L_{B22} through diode DB21. Current i_{LB22} decreases to zero at t2.

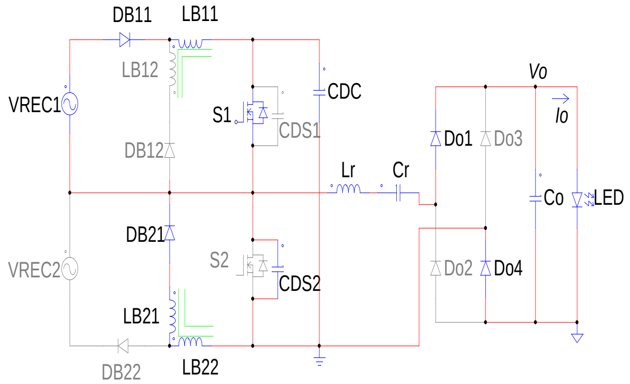

Fig. 4(b): Equivalent circuit for mode 2

Mode 3(t2≤t<t3; in Fig. 4(c)): Voltage source V_{REC1} provides energy to coupled inductor L_{B11} through diode DB11 and switch S1. Capacitors C_{DC} and C_{DS2} and resonant inductor Lr provides energy to capacitors Cr and Co and to the LED through diodes Do1 and Do4. At t3, the coupled-inductor current reaches its peak value and it is given as

$$i_{LB11-pk} = \frac{|\sqrt{2}v_{AC-rms}\sin(2\pi f_{AC}t)|}{2L_{B11}} DTs, \qquad (2)$$

where D and Ts are the duty cycle and period of the switch, respectively.

This mode ends when diode D_B12 becomes forward-biased at t3.

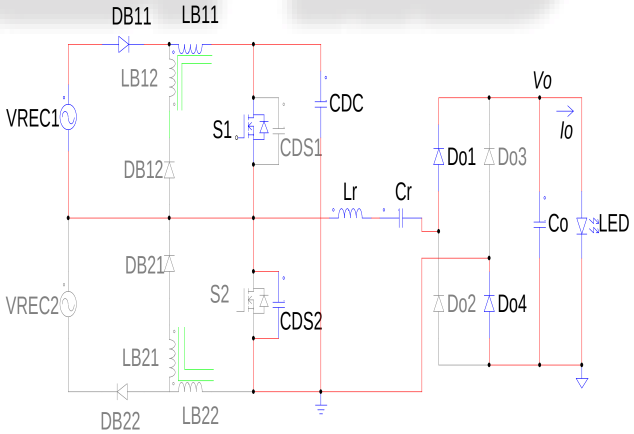

Fig. 4(c): Equivalent circuit for mode 3

Mode 4 (t3≤t<t4; in Fig. 4(d)): At t3 the switch S1 turns off. Capacitor C_{DS1} is energized by coupled inductors L_{B11} and L_{B12} through diode D_{B12}. The current i_{LB11} linearly decreases from its peak level and is expressed as

$$i_{LB11}(t) = \frac{V_{DC}}{2L_{B11}}(t - t_3), \qquad (3)$$

Capacitors C_{DC} and C_{DS2} and resonant inductor Lr provides energy to capacitors C_{DS1}, Cr, Co and to the LED through diodes Do1 and Do4. When the drain to source voltage v_{DS2} of S2 decreases to zero at t4, this mode ends.

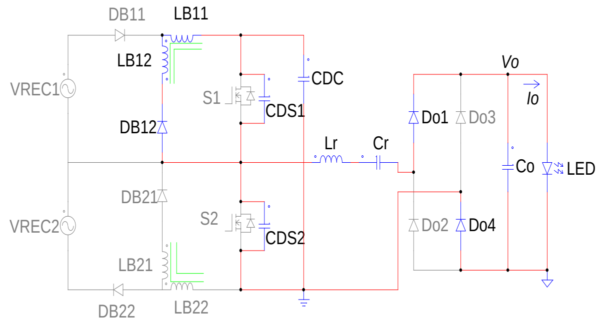

Fig. 4(d): Equivalent circuit for mode 4

Mode 5 (t4≤t<t5; in Fig. 4(e)): the diode of the switch is forward biased at t4. Capacitors C_DS2, Cr, Co and the LED are energized by resonant inductor Lr through diode of the switch and diodes Do1 and Do4. The coupled inductors L_B11 and L_B12 provide energy to capacitor C_DS1 through diode D_B12. S2 turns on with ZVS as drain to source voltage of switch goes zero at t5.

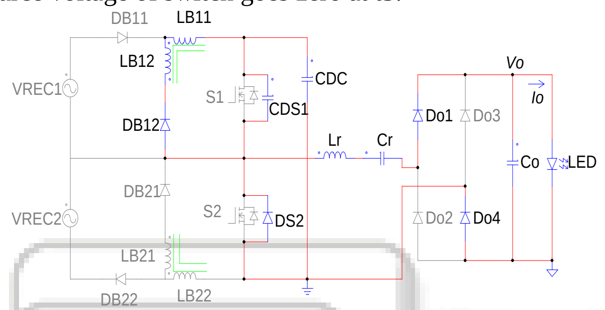

Fig. 4(e): Equivalent circuit for mode 5

Mode 6 (t5≤t<t6; in Fig. 4(f)): The coupled inductor L_B22 is energized by the rectified voltage source V_REC2 through diode D_B22and switch S2. The Lr capacitors C_DS1 and Co and the LED are energized by resonant capacitor Cr and DC-bus capacitor C_DC through diodes Do2 and Do3. This mode ends when current i_LB11 decreases to zero at t6.

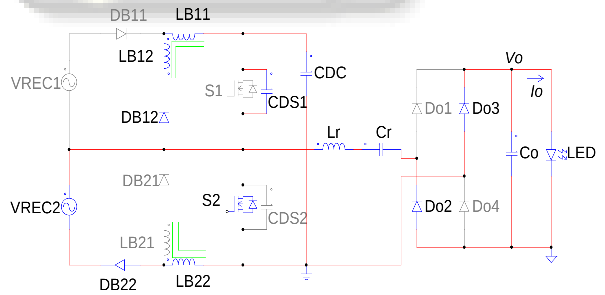

Fig. 4(f): Equivalent circuit for mode 6

Mode 7 (t6≤t<t7; in Fig. 4(g)): The coupled inductor L_B22 is energized by V_REC2 through diode D_B22 and switch S2. Resonant inductor Lr, capacitor Co and the LED are energized by resonant capacitor Cr. This mode ends when diode D_B21 is forward biased at t7.

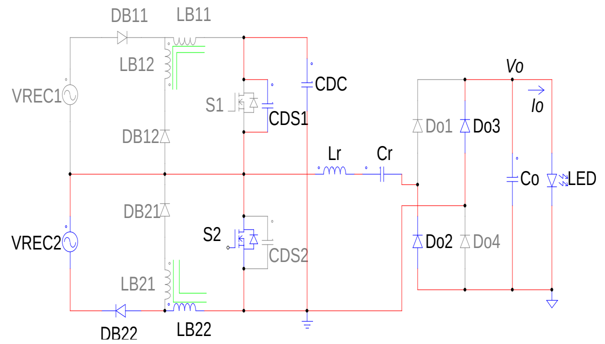

Fig. 4(g): Equivalent circuit for mode 7

Mode 8 (t7≤t<t8; in Fig. 4(h)): The switch S2 turns off at t7. The capacitor C_DS2 is energized by coupled inductors L_B21and L_B22 through D_B21. Lr, C_DS2, Co and LED are energized by resonant capacitor Cr through diodes Do2 and Do3. At t8 when drain to source voltage of S1 decreases to zero, this mode ends. The Mode 1 begins for the next high frequency switching period.

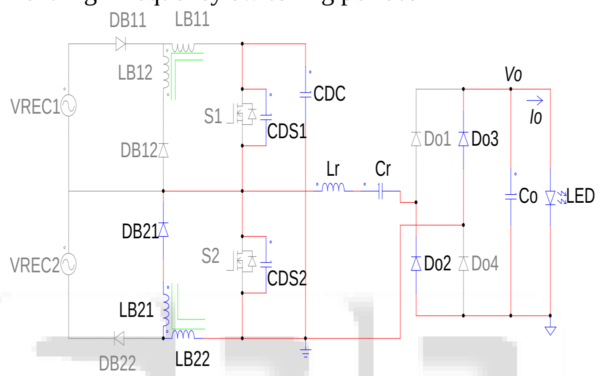

Fig. 4(h): Equivalent circuit for mode 8

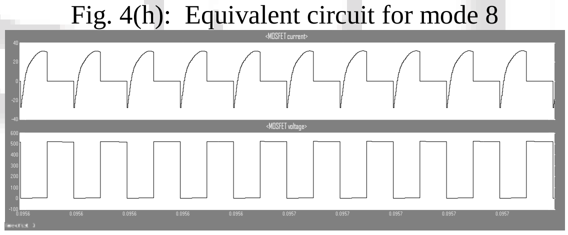

Fig. 5: Power switch S1 current and voltage waveform

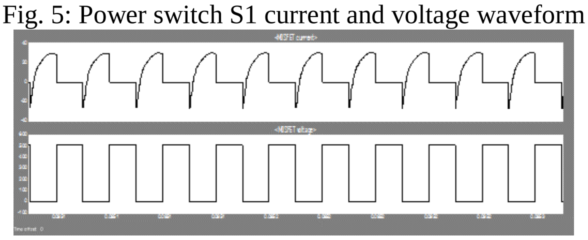

Fig. 6: Power switch S2 current and voltage waveform

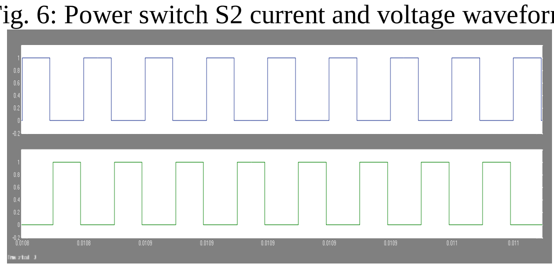

Fig. 7: Gate signal to switches S1 and S2 with duty cycle 0.45

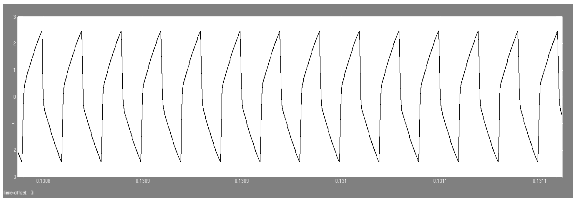

Fig. 8: Resonant inductor current waveform

IV. DESIGN EQUATIONS OF KEY PARAMETERS

A. *Coupled Inductors Lb11, Lb12, Lb21and Lb22:*

The coupled inductors are operated in DCM mode and their design equation is given below:

$$L_{B11} = L_{B12} = L_{B21} = L_{B22} = \frac{\eta . v_{ac-pk}^2 . D^2}{4 . f_{s} . P_0} \quad (4)\backslash$$

where v_{ac-pk} is the peak value of line voltage; η is the efficiency of the system; D is the duty cycle of the switch; f_s is the switching frequency; P_o is output power.

Referring to (1) with η of 0.85, v_{ac-pk} of 110√2 V, D of 0.45, Po of 165W and f_s of 50KHz, the value of coupled inductors are given by

$$L_{B11} = L_{B12} = L_{B21} = L_{B22}$$

$$= \frac{0.85(110\sqrt{2})^2 \, 0.45^2}{4.50K.165} = 126\mu H$$

B. *Resonant Inductor Lr And Resonant Capacitor Cr:*

The resonant frequency f_r is given by

$$f_r = \frac{1}{2\pi\sqrt{Lr.Cr}} \quad (5)$$

Switching frequency and resonant frequency are related as

$$f_s = 4 f_r \quad (6)$$

Quality factor Q_r is given by

$$Q_r = \frac{\sqrt{Lr}}{Ra\sqrt{Cr}} \quad (7)$$

where Ra is the equivalent output resistor, which can be expressed as

$$\text{Ra} = \frac{8Vo}{\pi^2 Io} \quad (8)$$

Combining (2) with (3), (4) and (5), the resonant capacitor *Cr and resonant inductor Lr* are given by

$$Cr = \frac{2}{RaQ_{L}f_s} \quad (9)$$

and

$$Lr = \frac{4}{\pi^2 f_s^2 Cr} \quad (10)$$

Referring to (8), with *Vo* of 235V and an *Io* of 700mA, the resistor *Ra* is given by

$$Ra = \frac{8.235}{\pi^2 700m} = 272.5\Omega.$$

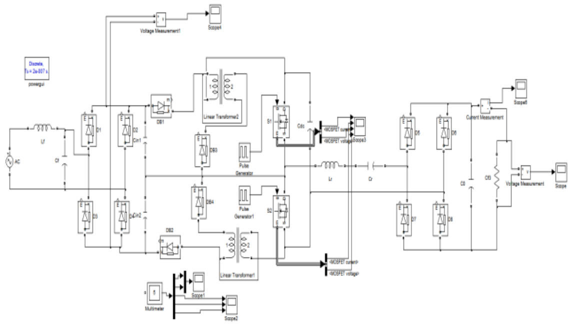

Fig. 9: MATLAB simulation for open loop

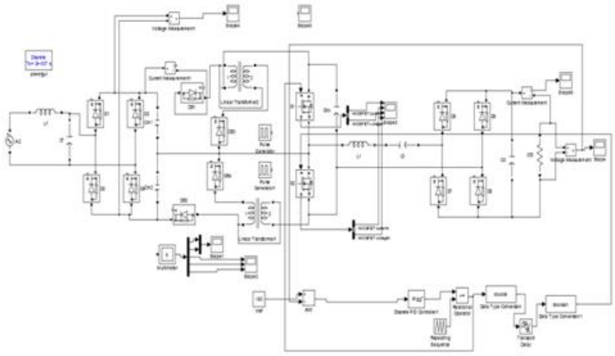

Fig. 10: Closed loop simulation of proposed topology

V. EXPERIMENTAL RESULTS

This paper proposes a LED driver with high power factor correction, low total harmonic distortion and switches are operated with zero voltage switching. Figure 11 shows the power factor correction at input side with power factor of 0.992 and figure 15 shows total harmonic distortion with distortion less than 7 % i.e.6.88 %. Figure 12 shows the ZVS condition where switches 1 and 2 are operating in zero voltage switching respectively. Figure 9 shows the MATLAB simulation for open loop proposed topology, figure 13 shows output voltage waveform i.e.235V, and figure 14 shows output current waveform i.e.701mA. Figure 10 shows closed loop simulation where output voltage is regulated by changing the duty cycle of the switches with the help of PI controller.

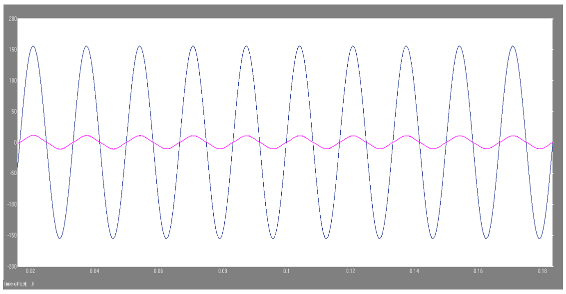

Fig. 11: Input utility voltage and current

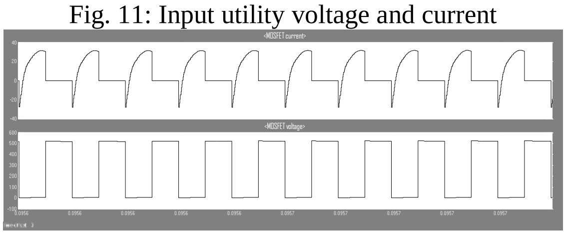

Fig. 12: Zero voltage switching condition

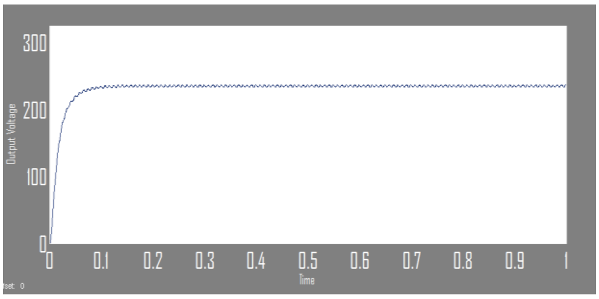

Fig. 13: Waveform of output voltage

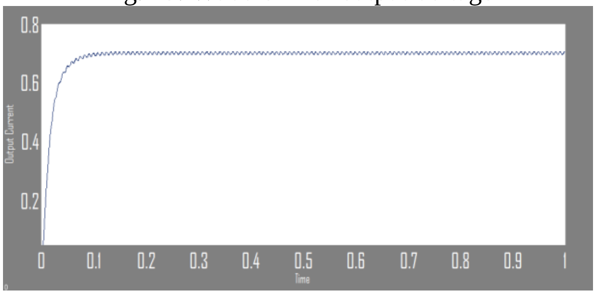

Fig. 14: Waveform of output current

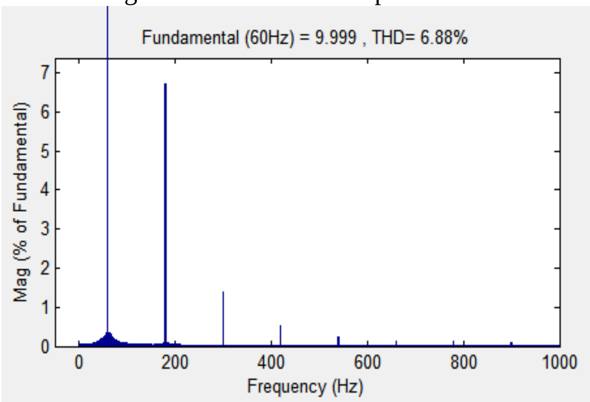

Fig. 15: Total harmonic distortion (THD) of input utility line current

Parameters	Value
Input Utility-Line voltage v_{AC}	110 V (rms)
Output Power P_0	165 W
Output Voltage V_0	235 V
Output Current I_0	701 mA

Table 1: Specifications Of The Proposed Single-Stage Led Driver

Components	Value
Capacitors C_{in1}, C_{in2}	330 nF
Inductors L_{B11}, L_{B12}, L_{B21}, L_{B22}	126 µH
Diodes D_{B11}, D_{B12}, D_{B12}, D_{B22}, D_{o1}, D_{o2}, D_{o3}, D_{o4}	MUR460
Switches S_1, S_2	STP20NM60
DC-Linked Capacitor C_{DC}	100 µF/450 V
Resonant Inductor *Lr*	162 µH
Resonant Capacitor *Cr*	1 µF/250V
Output Capacitor *Co*	220 µF/400V

Table 2: Specifications Of Components Utilized In Led Driver

VI. Conclusion

This paper proposes an interleaved LED driver with coupled inductor and LC resonant circuit. The proposed driver achieves high power factor, low THD and soft switching. A 165W prototype LED driver has been built and is tested for 110V input voltage. The results shows the power factor to be 0.992 and total harmonic distortion at input side current to be 6.88%, and zero voltage switching on power switches has also been achieved.

References

[1] E. F. Schubert, Light-emitting diodes, Cambridge University Press, 2006.
[2] "Energy-efficient solutions for offline LED lighting and general illumination," STMicroelectronics Brochure, pp. 1-27. http://www.mouser.com/pdfDocs/STMicro_OFFLINE GENERAL_ILLUMINATION_A .pdf
[3] "LED lighting solutions," ON Semiconductor, pp. 1-48, March 2013. http://www.onsemi.cn/pub_link/Collateral/BRD8034-D.PDF
[4] Y. S. Chen, T. J. Liang, K. H. Chen and J. N. Juang, "Study and implementation of high frequency pulse LED driver with selfoscillating circuit," in Proc. of IEEE ISCAS'11, pp. 498-501, 2011.
[5] C. S. Moo, Y. J. Chen and W. C. Yang, "An efficient driver for dimmable LED lighting," IEEE Trans. Power Electron., vol. 27, no. 11, pp. 4613-4618, Nov. 2012.
[6] H. L. Cheng and C. W. Lin, "Design and implementation of a high power-factor LED driver with zero-voltage switching-on characteristics", IEEE Trans. Power Electron., vol. 29, no. 9, pp. 4949-4958, Sept. 2014.
[7] G. Sauerlander, D. Hente, H. Radermacher, E. Waffenschmidt and J. Jacobs, "Driver electronics for LEDs," in Proc. of IEEE 41th IAS Annual Meeting, pp. 2621-2626, 2006.
[8] S. Y. R. Hui and Y. X. Qin, "General photo-electro-thermal theory for light-emitting diodes (LED) systems," IEEE Trans. Power Electron., vol. 24, no. 8, pp. 1967-1976, Aug. 2009.
[9] C. H. Chang, C. A. Cheng, M. Jinno, H. L. Cheng, "An interleaved single-stage LLC resonant converter used for multi-channel LED driving", in Proc. of IEEE ECCE-Asia IPEC-Hiroshima 2014, pp.3333-3340, 2014.
[10] J. Sebastian, D. G. Lamar, M. Arias, M. Rodriguez, and M. M. Hernando, "A very simple control strategy for power factor correctors driving high-brigtness LEDs," in Proc. of IEEE APEC'08, pp. 537-543, 2008.
[11] K. Zhou, J. G. Zhang, S. Yuvaraj and D. F. Weng, "Quasi-active power factor correction circuit for HB LED driver," IEEE Trans. Power Electron., vol. 23, no. 3, pp. 1410-1415, May 2008.
[12] X. Long, R. Liao and J. Zhou, "Development of street lighting system based novel high-brightness LED modules," IET Optoelectronics, vol. 3, no. 1, pp. 40-46, February 2009.
[13] S. Hu, "200W AC/DC LED Driver," Texas Instruments, pp. 1-4, November 2010. http://www.ti.com/lit/ml/slur086/slur086.pdf

