A New Non-Isolated High Power Factor White LED Driver for Street Light Applications

Alireza Hallajian Mofrad Kashani
Electrical Engineering Department,
Shahed University, Tehran, Iran
alirezahallajian@yahoo.com

Mahdi Akhbari
Electrical Engineering Department,
Shahed University, Tehran, Iran
akhbari@shahed.ac.ir

Pouya Amiri
Electrical Engineering Department,
Shahed University, Tehran, Iran
amiri.pouya@gmail.com

Abstract— **In this paper an integrated driver with only one switch and one capacitor for driving high brightness white light emitting diodes (HB-WLEDs) in street light applications has been proposed. The proposed driver in addition to providing high power factor at the input, features considerable more lifetime and compact size due to eliminating one capacitor compared with conventional circuit topologies for driving HB-WLEDs. Proper operation of the driver was certified through simulation process and laboratory test. In simulation process a commercially available LED with adopted linear model was used. Furthermore a laboratory prototype showed high input power factor in addition to proper operation of the driver.**

Keywords- White LEDs; Integrated LED driver; High Power Factor; High Efficiency; Long Lifetime

I. INTRODUCTION

Recently, High Brightness white Light Emitting Diodes (HB-WLEDs) are regarding as the best light sources owning to their salient features such as high efficacy, long lifetime, small size, high color rendering index, shock and vibration resistance and environmental friendliness over conventional light sources including incandescent, HID and fluorescent lamps [1-5]. The mentioned advantages of these light sources have made them favorable for different applications such as background lighting, display lighting, decorative lighting, interior lighting, outdoor lighting and street lighting [3].

As the available commercial LEDs consume only a few watts and their efficacy is approximately 75 Lm/W to 100 Lm/W [1], [5] LEDs should be connected in series and parallel in a fixture to get sufficient luminance. Due to electrical characteristic of nearly constant voltage of LEDs and the need of nearly DC current with low ripple for their proper operation, the requirement of a driver to provide desired DC voltage and current to the fixture from the input source exists. In street light applications the converter should supply the fixture with desired DC voltage and DC current from AC mains. It is notable that high current ripple flowing through LEDs in addition to lowering the output light quality, lessens the lifetime and efficacy of LEDs [7].

To obtain the outstanding features of LEDs in street light applications, the AC to DC converter should feature long lifetime and high efficiency as individual LEDs. Additionally, for the purpose of overall light source high efficiency and meeting mandated EN61000-3-2-C standard for applications where power rating is more than 25 Watts, drivers should have high power factor (PF) at the input [6].

Well designing of the converter with lowest possible power dissipating components along with high power factor can guarantee the high efficiency of the converter. To be able to use the long lifetime of HB-WLEDs, the converter lifetime should be as high as of the HB-WLEDs. The existence of large capacitor between two stages, named as storage capacitor, for supplying the output power in intervals when the instantaneous input power is less than the output power along with the output stage capacitor which has the role of eliminating output voltage ripple, are the main factors of limiting driver's lifetime. The lifetime of individual HB-WLEDs is around 50,000 hours in which their output light will reach 70% of their nominal output light [8], while the electrolytic capacitor lifetime is about 30,000 hours at the most [9].

Fig. 1 Shows the conventional configuration for driving high brightness LEDs comprising of two cascaded stages. Each stage is a high frequency switching power supply in which the first stage operates in discontinuous conduction mode (DCM) and the second stage operates in continuous conduction mode (CCM). Operation of the first stage in DCM ensures attaining high power factor and operation of second stage in CCM ensures delivering DC voltage and current to LED fixture with low ripple [6].

The conventional configuration shown in Fig. 1 suffers from large size, high cost and large number of components. Integrating stages in a single one and overcoming mentioned drawbacks, has been widely explored in different papers. In [6] different topologies such as flyback, SEPIC, buck-flyback, boost-flyback, resonance assisted buck and buck-boost has been pointed.

In this paper a new non-isolated integrated driver for driving HB- WLEDs in street light applications has been proposed. Comparing with Fig. 1, the first stage is the regular buck-boost converter and the second stage supplies the LEDs through an inductor. Sharing a common node between switches, enables integration of stages in just one with only one switch [3]. Lacking second stage capacitor along with single switch in proposed driver, gives the achievements of high

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efficiency and significant long lifetime. Sections I and II explain the input and output stage operations. Section III deals with integration and analysis of integrated driver. In Section IV, using an available commercial LED with an adopted linear model, the validity of analysis and proper operation of the driver has been explored.

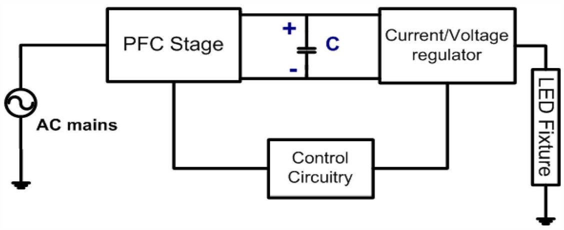

Figure 1. Conventional configuration for driving HB-WLEDs

II. INPUT STAGE

Compared with conventional configuration of driving HB-WLEDs, the first stage of the driver is buck-boost switching power supply. Fig. 2 shows the buck-boost converter schematic.

In Fig. 2 V_{in} is the rectified voltage of ac mains. As shown in Fig. 3 for achieving high power factor, the input stage inductor should operate in DCM. Considering Fig. 3 and Fig. 4 reveals that operation of the first stage in DCM makes the line averaged current sinusoidal just as the input line voltage. Moreover in DCM operation of input stage, the diode will turn off naturally which eliminates diode reverse recovery loss and helps to efficiency enhancement of the driver. t_d is the time in which the inductor discharges before starting a new switching cycle.

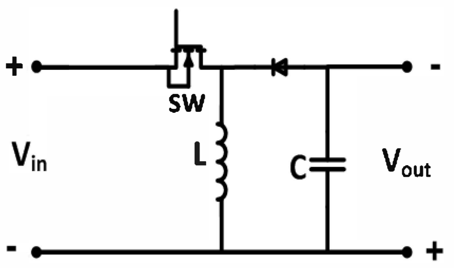

Figure 2. Buck-Boost converter schematic

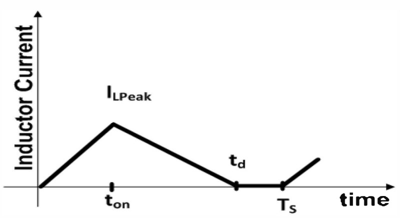

Figure 3. Inductor current in each switching cycle

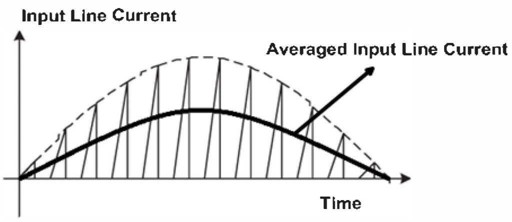

Figure 4. Line input current and it's averaged while operating in DCM

Inductor current can be mathematically expressed as (1).

$$i_L(t) = \begin{cases} \frac{V_m|sin(\omega t)|}{L} t & 0 < t < t_{on} \\ i_{Lpeak} - \frac{u_c}{L}(t - t_{on}) & t_{on} < t < t_d \\ 0 & t_d < t < T_S \end{cases} \quad (1)$$

In which

$$t_d = \frac{V_m}{U_c} t_{on} \quad (2)$$

$$i_{Lpeak} = \frac{V_m|sin(\omega t)|}{L} t_{on} \quad (3)$$

Line averaged current can be expressed as (4). t_{on} is replaced by DT_s, where D is the switch duty cycle.

$$\langle i_{Line} \rangle = \frac{1}{T_S}\frac{1}{2} i_{Line-peak} t_{on} = \frac{D^2 V_m}{2L_i f_s} sin\, \omega_{Line} t \quad (4)$$

III. OUTPUT STAGE

In [10], an electrolytic capacitor-less circuit for LED driving has been proposed. Schematic of the proposed circuit is shown in Fig 5.

The inductor of the output stage supplies LEDs and operates in CCM. Fig. 6 and Fig. 7 show the operation of output stage. Fig. 8 to Fig. 10 depicts the main waveforms of the stage. When the switch turns on, inductor current will increase linearly due to nearly constant input voltage across it. Input voltage will be provided by the first stage. When the switch turns off the inductor will discharge in LED Fixture and supplies it. Inductor current and its voltage waveforms are shown in Fig. 8 and Fig. 9. Fig 10 shows the current flowing through power switch.

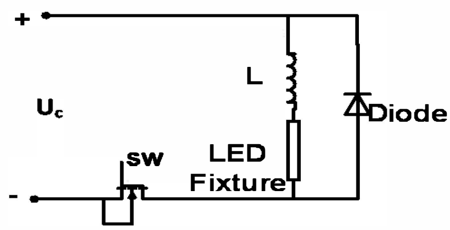

Figure 5. Output stage schematic

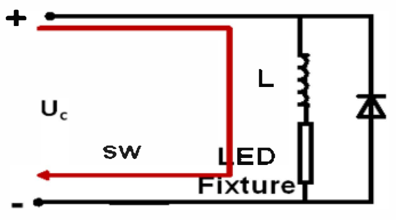

Figure 6. charging of inductor during 0<t<ton

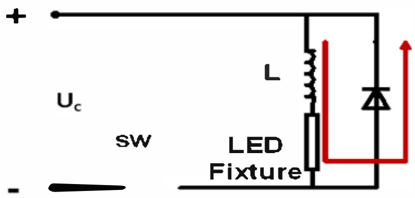

Figure 7. discharging of inductor through LEDs during ton<t<TS

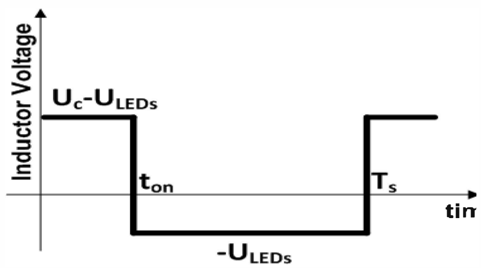

Figure 8. Inductor voltage of output stage

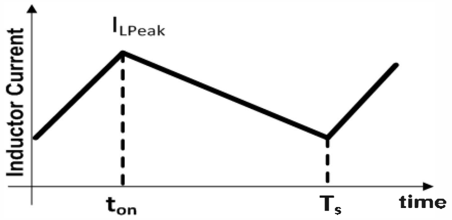

Figure 9. Inductor current of output stage

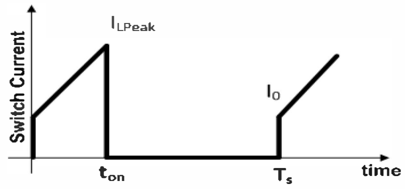

Figure 10. Switch current of output stage

(6) to (8) show the corresponding equations of Fig. 8 to Fig 10.

$$u_L(t) = \begin{cases} U_c - U_{LEDs} & 0 \le t \le t_{on} \\ -U_{LEDs} & t_{on} \le t \le T_s \end{cases} \tag{6}$$

$$i_L(t) = \begin{cases} i_0 + \frac{u_c - u_{LEDs}}{L} t & 0 \le t \le t_{on} \\ i_{max} - \frac{u_{LEDs}}{L}(t - t_{on}) & t_{on} \le t \le T_s \end{cases} \tag{7}$$

$$i_{sw}(t) = \begin{cases} i_0 + \frac{u_c - u_{LEDs}}{L} t & 0 \le t \le t_{on} \\ 0 & t_{on} \le t \le T_s \end{cases} \tag{8}$$

(9) to (13) show that the second stage operation is the same as the well-known buck converter.

$$D = \frac{t_{on}}{T_s} \tag{9}$$

Referring to (7) we have

$$i_{max} = i_0 + \frac{u_c - u_{LEDs}}{L} t_{on} \tag{10}$$

$$i_{max} = i_0 + \frac{u_{LEDs}}{L} t_{off} \tag{11}$$

From (10) and (11) and using (12), input-output relation can be expressed as (13).

$$T_S = t_{on} + t_{off} \tag{12}$$

$$D = \frac{u_{LEDs}}{u_C} \tag{13}$$

IV. INTEGRATION OF STAGES AND ANALYSIS OF INTEGRATED DRIVER

Fig.11 shows the cascaded connection of stages. Sharing a common node between switches enables the integration of stages in just one stage. Eliminating one of the power switches, in addition to reducing the size and cost of the driver, will significantly improve its efficiency by reduction of one switch losses. Furthermore the integration will make the control circuitry simpler and more reliable. Fig. 12 shows the integrated driver with only one capacitor. Comprising of just one capacitor and one switch which results in considerable long lifetime and high efficiency has made this driver so desirable for the purpose. Non-floating power switch in the integrated driver is another advantage of the proposed driver.

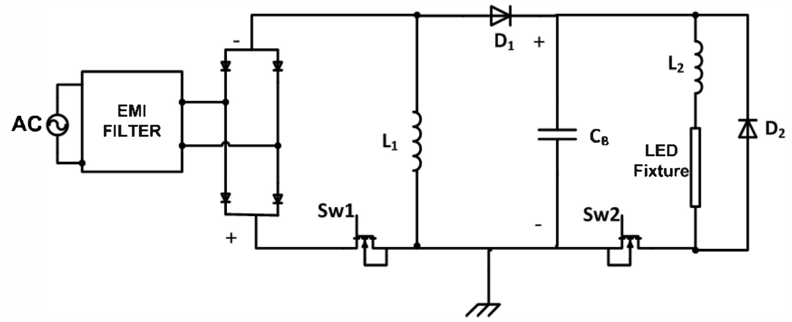

Figure 11. Cascaded stages of driver

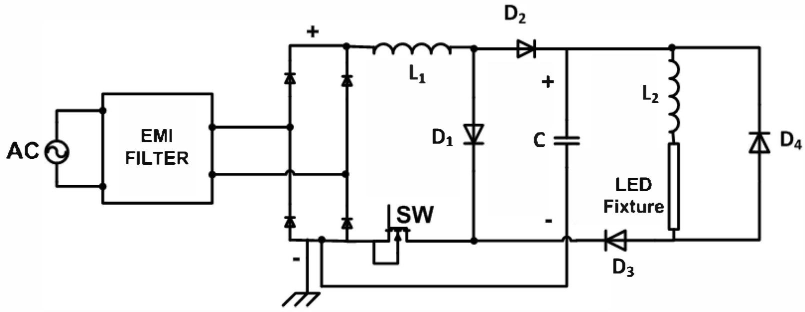

Figure 12. Schematic of the proposed driver

In [9] it is shown that injecting third harmonic current from input current can reduce the storage capacitor size by making the instantaneous input power waveform closer to the output constant power while meeting the required standard of high power factor.

Due to comprising two inductors in the final driver in which the first one operates in DCM and the second one operates in CCM, there are three intervals in each switching cycle.

Fig. 14 to Fig. 15 shows the circuit connection in three intervals of operation during one switching cycle. As shown in Fig. 14, when the switch is turned on, input stage inductor will charge linearly due to nearly constant voltage across it(because of high switching frequency, input voltage can be assumed to be constant in each switching cycle). In this interval, the capacitor charged from previous cycle, will supply LED fixture.

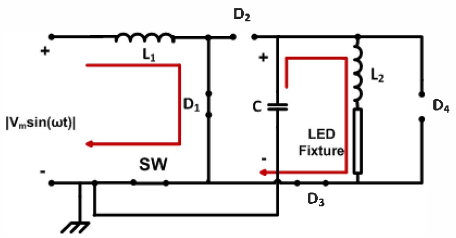

Figure 13. Operation of driver for 0<t<ton

Next interval begins with switch turning on as shown in Fig. 15. In this manner, input stage inductor will discharge through C and charges it. In this case LED Fixture would be supplied through output inductor (L_2). Third interval as shown in Fig. 16 exists due to fully discharge of L_1 previous to beginning of the next switching cycle.

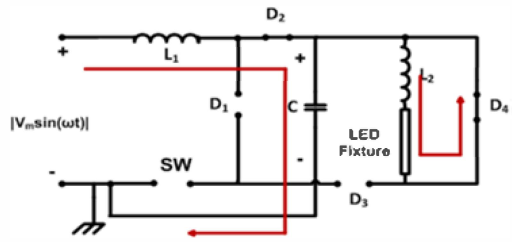

Figure 14. Operation of driver for 0<t<td

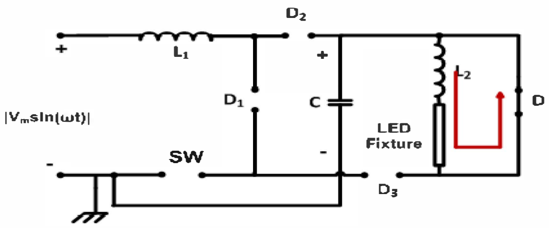

Figure 15. Operation of driver for td<t<TS

V. DESIGN PROCEDURE

A. Input inductor(L_1)

Using (4), and assuming η as the driver efficiency, the input inductor can be derived from power equilibrium of $P_i=P_o$. In this case input inductance can be expressed as (16).

$$P_{in} = \frac{1}{2} V_m \langle i_{line} \rangle_{peak} = \frac{D^2 V_m{}^2}{4 L_i f_s} \quad (14)$$

$$P_O = \eta P_{in} \quad (15)$$

$$L_i = \frac{D^2 V_m^2}{4 P_O f_s} \eta \quad (16)$$

B. Capacitor Design

Capacitance of the driver can be derived from ac current component flowing through it. Capacitor current is the same as D_2 current when switch is turned off. Capacitance can be calculated from (23).

$$\Delta V_{B-LF} = 2 \langle i_{D2} \rangle_{peak} X_c \quad (17)$$

$$\langle i_{D2} \rangle = \frac{1}{T_S} \frac{i_{D2peak} t_d}{2} \quad (18)$$

$$t_d = \frac{V_m}{U_c} t_{on} \quad (19)$$

$$i_{D2peak} = i_{L1peak} \quad (20)$$

$$\langle i_{D2} \rangle = \frac{D^2}{2 u_c f_s L_i} V_m^2 \left(\frac{1}{2} - \frac{1}{2} \cos 2\omega_{Line} t \right) \quad (21)$$

$$\langle i_{D1} \rangle_{ac} = \frac{D^2}{4 u_c f_s L_i} V_m^2 \cos 2\omega_{Line} t \quad (22)$$

$$C = \frac{D^2 V_m^2}{8 \pi u_c L_i \Delta U_{c-LF} f_s f_{Line}} \quad (23)$$

In the capacitor equation f_s and f_{line} are switching and line frequencies respectively. U_c represents the capacitor voltage.

C. OUTPUT INDUCTOR DESIGN

According to Fig. 9 the inductor s current ripple -which is the same as LED Fixture current ripple- can be expressed as (24). From (25) with a pre-determined ripple current, the inductance can be calculated.

$$\Delta i_{LEDs} = \frac{u_{LEDs}}{L} t_{off} \quad (24)$$

$$L = \frac{u_{LEDs}}{\Delta i_{LEDs}} t_{off} \quad (25)$$

D. DUTY CYCLE LIMITATION

Duty cycle limitation should be considered due to preventing L_1 from running into CCM. L_1 operates as a buck-boost converter inductor. Thus duty cycle limitation for switch can be expressed as:

$$D_{Limit} = \frac{1}{1 + {}^{V_m}/_{V_c}} \quad (26)$$

VI. SIMULATION AND EXPERIMENTAL RESULTS

In this section to explore the accuracy of analysis and operation of the converter an available commercial LED with adopted linear model presented in [11] has been selected to test by proposed driver. The selected wattage to test the driver was 70 watts to comply with high power requirement in street light applications. The 70 watts fixture is a combination of 60 series 1-watts power LED. The driver was simulated using data presented in table 1. The values were derived from section 5, to achieve 0.35A and 200V for the LED Fixture and a high power factor at the input of driver. Meanwhile the load model was a 170 volts DC voltage connected in series with an 87Ω resistor exactly as presented in [11]. Input voltage was assumed to be $220\sqrt{2} \sin(100\pi t)$.

TABLE1. PARAMETER VALUES IN SIMULATION PROCESS

Parameters	Values
EMI Inductor	22nH
EMI Capacitor	100nF
Input Stage Inductor	0.55mH
Output Stage Inductor	30mH
Capacitance	40µF
Switching Frequency	100khz
Switch Duty Cycle	0.3

It is considerable that in street light applications due to being non-attachable by public, non-isolated drivers can satisfy safety regulations but replacing out of order drivers can cause much trouble. Therefore long lifetime plays an important role in design of driver for street light applications. Comprising only one capacitor with small size can warrant its long lifetime.

Fig. 17 shows LED Fixture and capacitor voltages. Fig.18 shows the LED Fixture current. Fig. 19 shows the input line current and line input voltage. To assure high input power factor, line input current harmonics should be evaluated. Fig. 20 shows the value of line input current harmonics and their high compliance with IEC-EN61000-3-2-C standard.

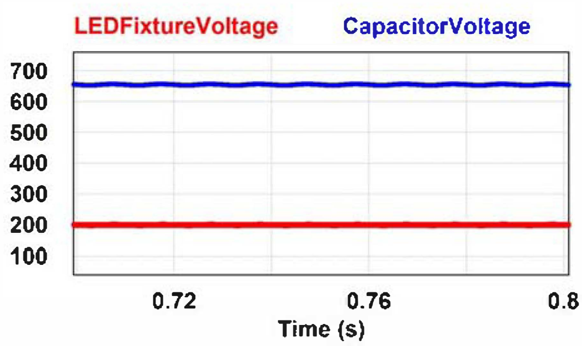

Figure 16. Capacitor (blue) and LED Fixture Voltages (red). (1V/Div for both)

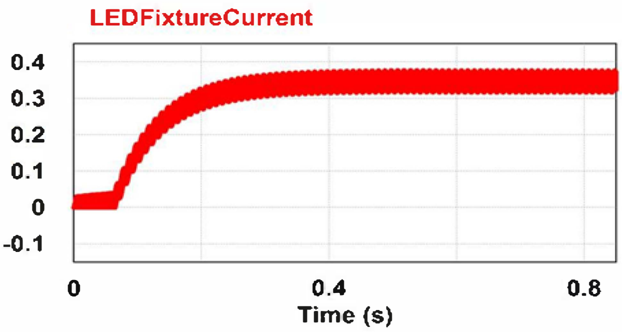

Figure 17. LED Fixture current. (1V/Div)

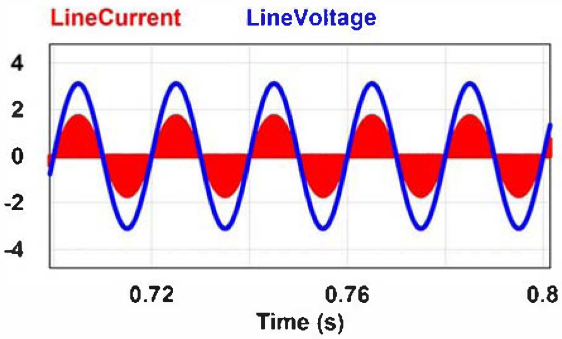

Figure 18. Input voltage (blue) and input current (red).
(100V/Div for voltage and 1V/Div for current)

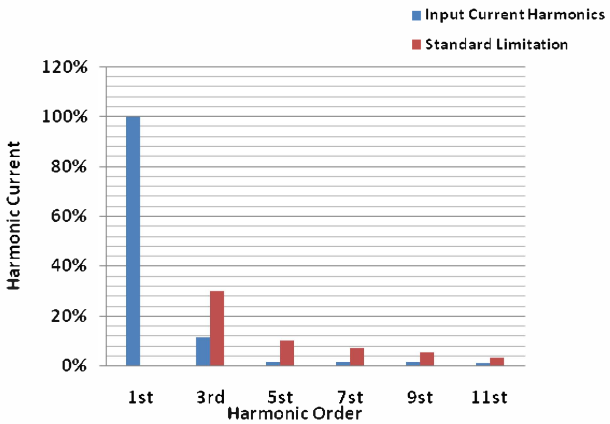

Figure 19. Comparison of input current harmonics with IEC- EN61000-3-2-C standard limitations

In order to investigate the practical operation of the proposed driver, a laboratory prototype was built. The aim of the experimental test, was obtaining an output voltage of about 30V and more importantly was exploring PFC operation of the circuit. In the prototype, the LED Fixture includes 9- series 1watt LED supplied with 50V input peak voltage which is equivalent to real 70watts fixture with $220\sqrt{2}$V input peak voltage. Fig. 20 shows the measured output voltage and Fig. 21 illustrates very high PF achievement (measured input voltage and current. Again it should be noted that in the experimental test the input peak voltage was considered 50V to comply with input-output voltage ratio for 70 watts simulated fixture.

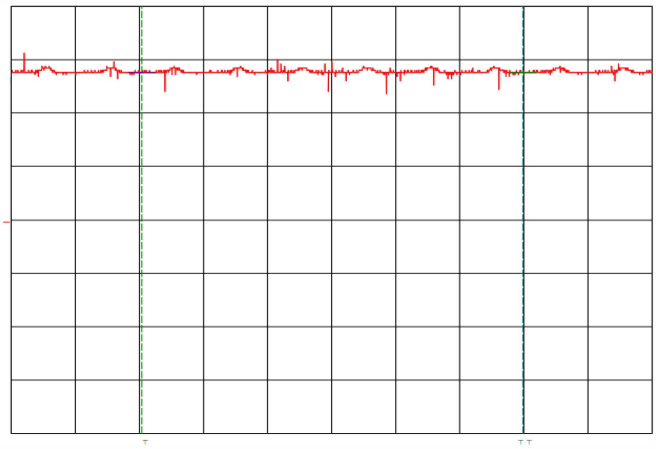

Figure 20. Fixture voltage.
(10V/Div for voltage and 10msec/Div for time axes)

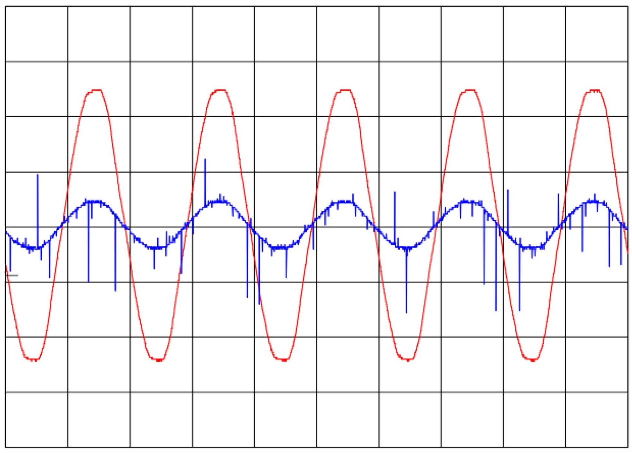

Fig 21. Experimental input voltage(red) and input current(blue).
(20V/Div for voltage and 0.1V/Div for current axes, Time/Div=10msec)

VII. CONCLUSION

In this paper a new high efficiency, high power factor driver with significant long lifetime for street light applications has been proposed. The proposed driver is based on cascade connection of two switching stages. First stage is a regular buck- boost converter, while the second supplies the LED fixture through an inductor. Integration of stages in just one stage, results in high efficiency and small size of the driver. Furthermore comprising just one capacitor in the driver warrants its long lifetime and makes it desirable for street light applications. Experimental and simulation results confirmed proper operation of the driver along with high power factor at the input.

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