High efficient single stage Cuk LED driver for universal input voltage applications with improved power quality

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Bridgeless positive output Cuk LED driver operated under universal supply (90 V to 240 V) voltage for indoor applications with improved AC source power quality has been presented. The undesirable harmonic content in the supply current due to the operation of conventional diode bridge rectifier (DBR) based two stage LED driver is greatly reduced by the proposed single stage (bridgeless) LED driver with very simple control circuit. Therefore, high efficient operation along with low total harmonic distortion (THD) and high power factor can be acquired. Performance of the Cuk LED driver has been analysed under various LED load power provided with universal supply voltage in simulation study. Experimental results agree with the simulation results. The results guarantee the stable operation of LED driver with regulated DC link voltage and upgraded power quality satisfying IEC 61000-3-2 class C standards.

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Keywords: Light Emitting Diode, Power factor, Source current harmonics, THD, Universal supply voltage

1. Introduction

LED lighting technology has become the most attractive trend in the implementation of indoor/outdoor lighting, commercial lighting, hospital lighting, residential and traffic lighting, street/security lighting etc in the recent days [1-2]. There are various key factors like prolonged durability, eco-friendly, cost-effective, fast response, high brightness, compact, improved luminous efficacy, low power consumption has impressed many researchers to choose LED lights in many applications [3]. A lot of research works have been done for the improvement of performance of LED light by improving its efficiency and brightness [4-5].

But, few researchers focus on the eradication of power quality issues on supply side while using LED lights. As LED driver operates on DC voltage, an AC to DC conversion stage is mandatory. For this purpose, a DBR along with huge capacitor in order to produce pure DC is most commonly employed. Fig. 1 shows the measured THD and power factor (PF) with the relative source current/voltage waveforms for DBR with bulk DC capacitor set up. This assembly is used to pollute supply current with very high harmonic distortions and produce very low power factor [6]. Therefore, Power Factor Correction [PFC] which contains a DC-DC converter followed by DBR [two-stage conversion] must be needed for improving power quality at AC source [7]. PFC must be given much importance as all the loads connected to a DC bus will be affected due to the impact of harmonic polluted load connected to the same DC bus. Especially, sensitive loads are fully got damaged and it leads to mal-function of devices/equipment. Two –stage AC-DC LED driver with converter topologies like flyback, buck, zeta, Cuk, boost, SEPIC, three level boost converter are used as PFC converters [8-15, 28-29].

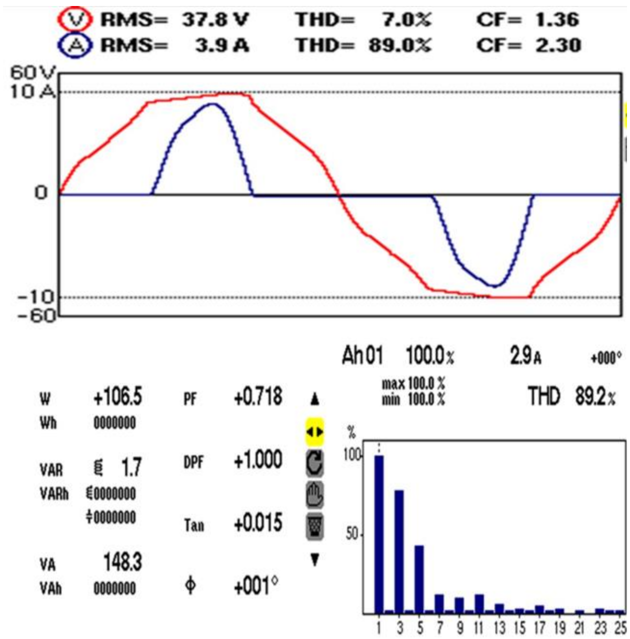

Fig. 1. Measured THD and PF for DBR with bulk capacitor

As per IEC 61000-3-2 class C standards, LED drivers are enforced to maintain power factor value equal to [or] greater than 0.9, with restricted source current THD at supply side [14,18]. The convectional bridge rectifier for DC-DC power converter topology provides better power conditioning but it develops more conduction and switching losses. During each conduction period, the number of power devices are being turned ON is more thereby efficiency gets lowered and hence cost of the system increases. Electromagnetic interference (EMI) is created due to generation of pulsating current from DBR.

In order to overcome these limitations, bridgeless single stage PFC converter topologies have been emerged [18-25]. As only half of the total current is being passed through the devices, bridgeless converter circuit minimizes the conduction loss to a greater extent. Also, when operated in DCM, control circuit becomes much simpler since there exists only mono voltage loop. Thus, reduction in number sensing parameters leads to cost-effective control circuit. Moreover, DCM provides way for achieving inherent power factors naturally [18]. Bridgeless boost PFC converters have been developed which can operate either in CCM/DCM. But the major issues regarding boost type PFC is i) high start-up/overload in rush current ii) magnitude of output voltage is always higher than provided supply voltage [21]. Bridgeless buck type PFC converters have been preferred as in [22]. Highly distorted and irregular shaping of line current are the serious drawbacks regarding buck PFC converter. Here, magnitude of output voltage obtained is always lesser than that of applied input voltage [23]. Regarding buck boost type converters, bridgeless, SEPIC and Cuk PFC converters have been used.

Number of research works using bridgeless SEPIC rectifier with improved efficiency as in [26-27] are applicable for low to high power applications. Yet, the usage of very large inductance for suppressing inductor current ripple restricts the usage of bridgeless SEPIC in many sensitive applications. Unlike these buck, boost and SEPIC rectifiers, Cuk PFC converters possess several merits like very less input/output current ripples, very small EMI filter, capable of withstanding high start UP/overloads in rush current. Moreover, it is easier to implement isolation [21,23]. Generally, Cuk converter produces negative output voltage.

This paper presents the novel bridgeless type single switch Cuk PFC converter fed LED driver for indoor/outdoor lighting operated under universal supply voltage. The proposed LED driver needs no inverse amplifier circuitry for generation of positive load voltage. A very simplified control circuitry with PI voltage controller is provided to regulate LED load voltage. In addition, reduced supply current harmonic distortion [less than 5%] with unity power factor is achieved. Hence, regulated DC voltage for LED driver along with better input side power quality is achieved using this single stage proposed LED driver.

2. Circuit description

The power circuit of proposed single switch Cuk LED driver with the schematic block diagram of simple control circuit is presented in Fig. 2. The control circuit needs only single parameter sensing as the Cuk LED driver operates in DCM. An analogy is made between the desired LED driver voltage and the measured LED driver voltage. The difference in voltage is processed by PI controller to generate gate pulse for MOSFET with the help of ramp signal. The desired switching frequency is achieved by proper ramp signal generation. With this simple control circuit, the satisfactory results of improved power quality (Less THD, High Power Factor) are acquired in the input side AC supply. Rated LED power is 100 W. Rated AC supply voltage is 120 V.

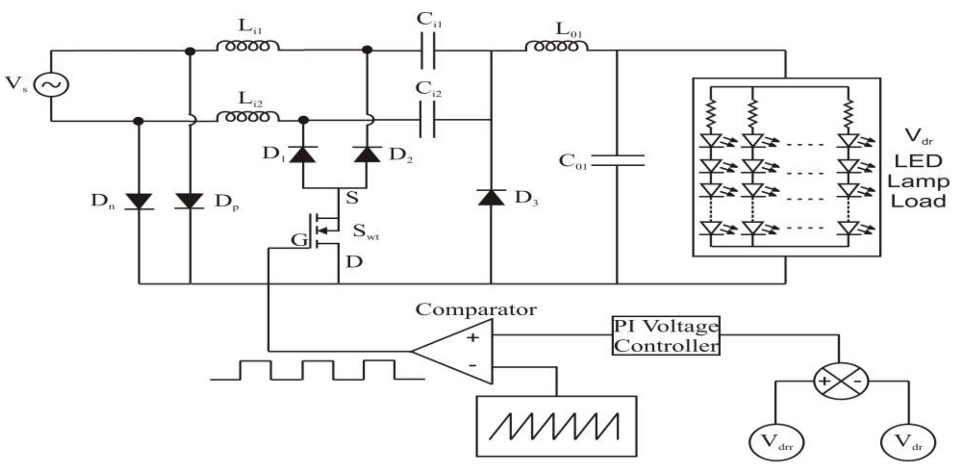

Fig. 2. Proposed single switch Cuk LED driver with the schematic control block diagram

The upcoming section describes the three operating modes of Cuk LED driver.

3. Operation modes

The time period of t_a – t_b (as seen in Fig. 6) corresponds to mode (a) as shown in Fig. 3. During this time period (t_a – t_b), the diode D_p gets forward biased and the current flows through the switch S_{wt} and charge the inductors L_{i2} and L_{01} with diode D_2 ON. Hence, voltage across both input and output inductors will be equivalent to AC supply voltage.

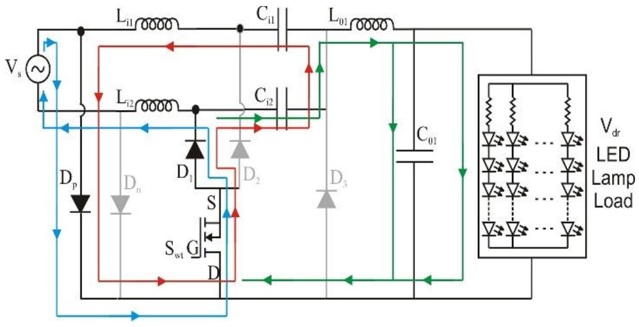

Fig. 3. Mode I operation of Bridgeless Cuk LED driver

The corresponding current equations are,

$$\frac{di_{L_{i2}}}{dt} = \frac{V_s(t)}{L_{i2}}$$

$$\frac{di_{L_{01}}}{dt} = \frac{V_s(t)}{L_{01}}$$

The time period of $t_b - t_c$ belongs to mode (b) as shown in Fig. 4. During this mode, switch S_{wt} is turned OFF and the diodes D_3 and D_p are turned ON, as the inductors L_{i2} and L_{01} being discharged.

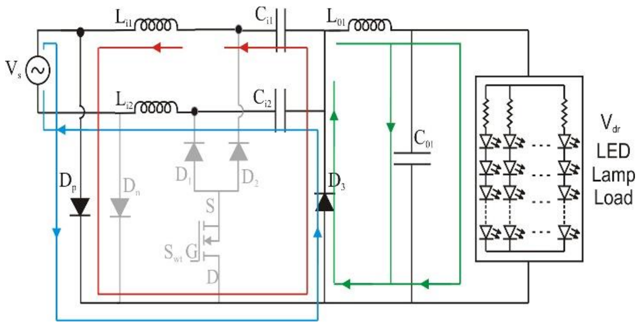

Fig. 4. Mode II operation of Bridgeless Cuk LED driver

The relative current equations are,

$$\frac{di_{L_{i2}}}{dt} = \frac{-V_s(t)}{L_{i2}}$$

$$\frac{di_{L_{01}}}{dt} = \frac{-V_{dr}}{L_{01}}$$

In the time period of $t_c - t_d$ ie., mode (c) as shown in Fig. 5, both inductors L_{i2} and L_{01} act as sustained current source and hence voltage across them will be '0'. Freewheeling operation happens in this mode.

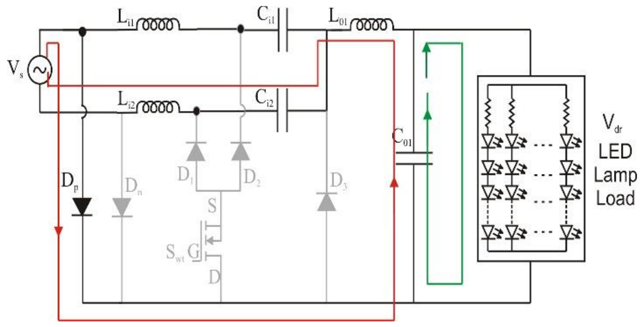

Fig. 5. Mode III operation of Bridgeless Cuk LED driver

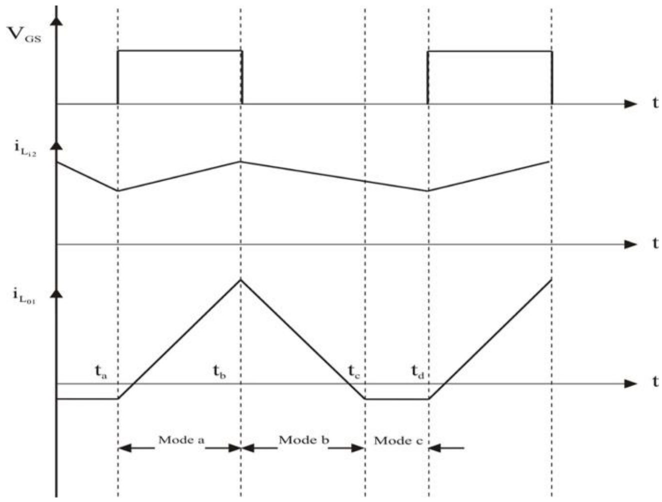

Fig. 6. Theoretical Inductor current waveforms of bridgeless Cuk LED driver

The components in the single stage Cuk LED driver have been designed as per the following equations.

Output Voltage,

$$V_{dr} = \frac{V_{in}}{1-d} \; ; \; V_{in} = \frac{2V_m}{\pi}$$

Input Inductors,

$$L_{i1} = L_{i2} = \frac{V_s^{\,2}}{2 f_{swt}} \left[\frac{I_{dr}}{V_m + V_{dr}} \right]$$

Output Inductor,

$$L_{01} = \frac{V_s . I_{dr}}{2\sqrt{2}\, f_{swt}} \left[\frac{V_{dr}}{2V_m + V_{dr}} \right]$$

Input Capacitors,

$$C_{i1} = C_{i2} = \frac{P_{dr}}{2 f_{swt} \left[V_m + V_{dr} \right]^2}$$

Output Capacitor,

$$C_{01} = \frac{I_{dr}}{2\omega\Delta V_{dr}}$$

where, V_s – AC supply voltage, V_m – Maximum value of AC supply voltage, f_{swt} – Switching frequency, V_{dr} – LED driver voltage, I_{dr} – LED driver current, P_{dr} – LED driver power, d – duty cycle. The design values of above mentioned components of LED driver are tabulated in Table 1.

Table 1. Ratings of Cuk LED driver components

Cuk LED Driver components	Ratings
Input inductors (L_{i1}, L_{i2})	5 mH
Output inductor (L_{01})	50 µH
Input capacitors (C_{i1}, C_{i2})	220 nF
Output capacitor (C_{01})	2200 µH

4. Simulation study and analysis of CUK LED driver

The performance of the proposed LED driver under universal supply voltage are analysed in both simulation and experimental study. Supply voltage/ current waveforms at 120 Vrms voltage under rated LED driver voltage along with the corresponding FFT analysis of input AC current is shown in Fig. 7 and Fig. 8.

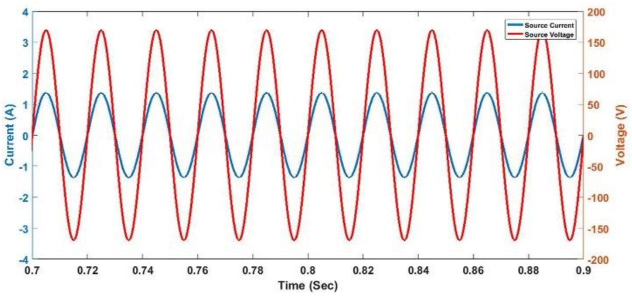

Fig. 7. Supply voltage/ current waveforms at 120 V rms voltage under rated LED driver voltage

With DCM operation, PF nearer to unity is intimately achieved since both the source waveforms are in phase as seen in Fig. 7.

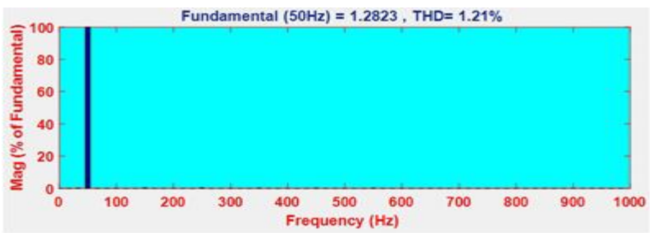

Fig. 8. FFT analysis of input AC current (V_{rms}=120 V)

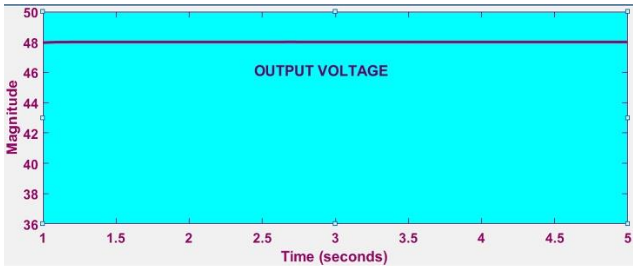

Fig. 9. Regulated LED driver voltage (V_{rms}=120 V)

Also, very less source current THD of 1.21% is attained (as inferred from Fig. 8). Regulated LED voltage of 48 V is obtained which is shown in Fig. 9. In the same manner, supply voltage of 240 V is applied to the LED driver and the relative waveforms and FFT analysis are depicted in Fig. 10 and 11.

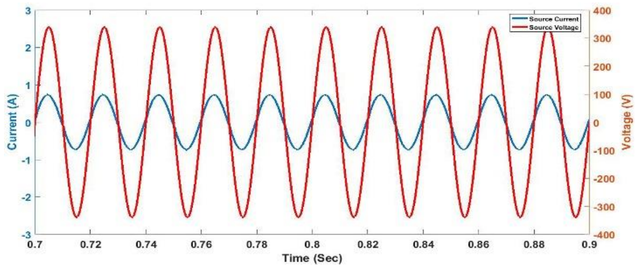

Fig. 10. Supply voltage/ current waveforms at 240 V rms voltage under rated LED driver voltage

Improved power quality with 0.47% THD and unity PF are obtained for the 240 V input supply voltage. Also, well regulated LED driver voltage of 48 V is obtained in this case as shown in Fig. 12.

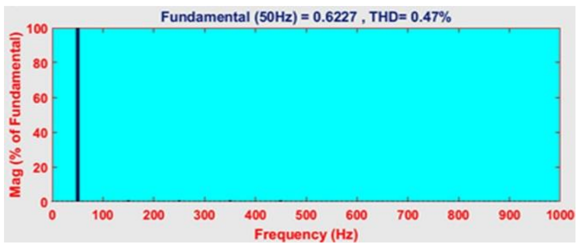

Fig. 11. FFT analysis of input AC current (V_{rms}=240 V)

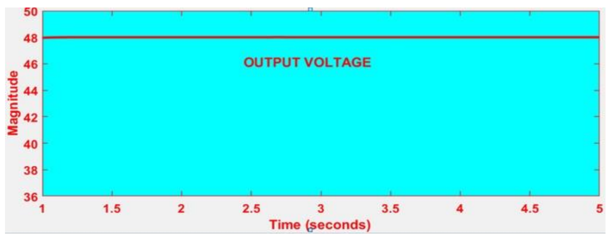

Fig. 12. Regulated LED driver voltage (V_{rms}=120 V)

The following graphical representation of supply current THD values and the input PF values for wide range of LED driver power under universal supply voltage variations are shown in Fig. 13 and Fig. 14.

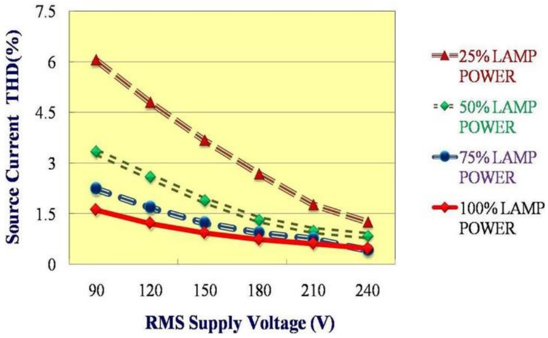

Fig. 13. Supply current THD values for wide range of LED driver power under universal supply voltage variations

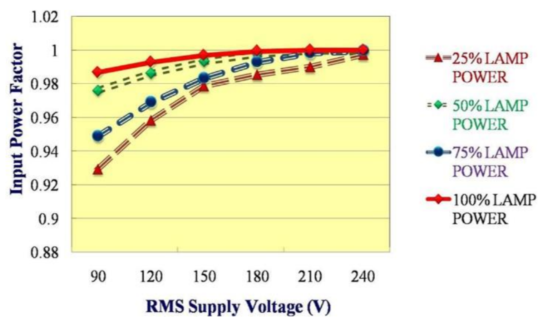

Fig. 14. Input PF values for wide range of LED driver power under universal supply voltage variations

The obtained THD and PF values are within the IEC 61000-3-2 class C standards. At rated driver power, very low THD values between 0.47 % and 1.61% are achieved for 90 V to 240 V AC voltage variations. Also, PF values range between 0.9868 and 1 which are almost closer to unity is achieved for 90 V to 240 V variations of supply voltage at rated LED driver power. Minimum value of 0.47 % THD with the maximum of 6.05 % is achieved for different LED load power (100 W to 25 W) under universal supply voltage variations (90 V to 240 V). PF value of 0.9294 as minimum value with the maximum of unity PF is achieved for different LED load power (100 W to 25 W) under universal supply voltage variations (90 V to 240 V). Thus, the proposed LED driver provides enhanced power quality at ac mains. Regulated LED load voltage of 48 V is obtained for all load power and supply variations.

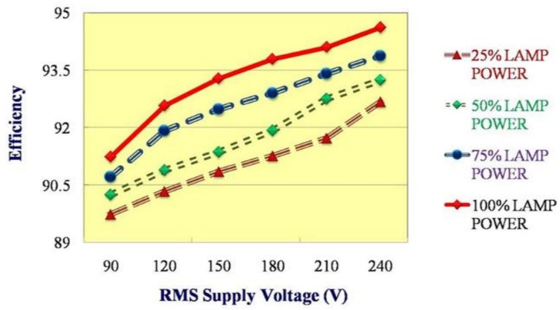

Fig. 15. Efficiency values for wide range of LED driver power under universal supply voltage variations

Moreover, increased efficiency of 94.61 % is acquired with this LED driver. The efficiency curve for different load/supply variation is given in Fig. 15. Least efficiency of 89.74% is achieved at supply voltage of 90 V at 25 W LED load power and best efficiency of 94.61% is achieved at supply voltage of 120 V at 100 W LED load power.

5. Experimental Verification of Cuk LED driver

THD and PF values of 1.618%, 0.984% and 0.9921, 0.9994 are taken using power quality analyser for 120 V and 240 V rms supply voltage at rated LED load power are given in Fig. 17 and Fig. 18. Experimental AC voltage/current waveforms are also given in Fig. 17 and Fig. 18 respectively. The experimental driver voltage of 48 V is acquired for both supply voltages of V_{rms} equal to120 V and 240 V which can be seen from Fig. 19.

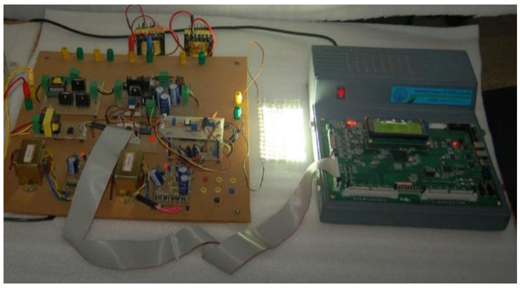

Fig. 16. Prototype of 100 W LED driver setup

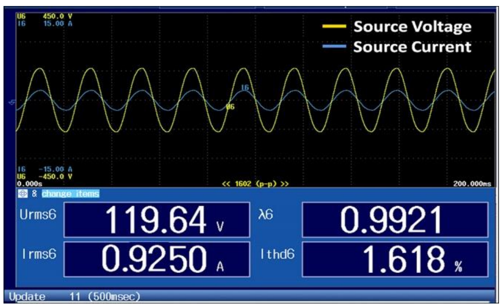

Fig. 17. Experimental AC voltage/current waveforms with relative power quality analysis (V_{rms} =120 V)

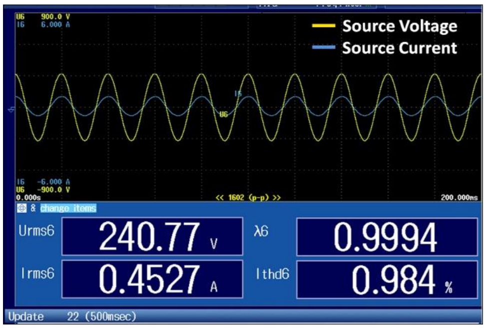

Fig. 18. Experimental AC voltage/current waveforms with relative power quality analysis (V_{rms} =240 V)

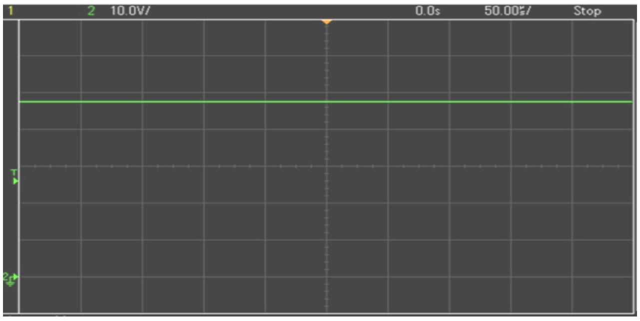

Fig. 19. Experimental LED driver voltage waveform (V_{rms} =120 V, 240 V)

6. Conclusions

A new bridgeless Cuk LED driver with simple closed control for universal supply voltage applications has been presented in this paper. Poor power quality at input AC supply due to LED driver is eradicated by proper control circuit. Evaluation of Cuk LED driver for universal input voltage (90 V – 240 V) under wide LED load power has been analysed. Reduced supply current THD of 0.47% and unity PF along with 94.61% efficiency are attained using this single stage Cuk LED driver. Component ratings are reduced to half the value as compared to conventional two stage PFC converter. Due to DCM operation, conduction/switching losses are greatly reduced and hence efficiency gets improved. Experimental set up is built and the results are validated with the simulation one.

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