Bridgeless Buck-Boost PFC Converter for Multistring LED Driver

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***Abstract*— In this paper, a bridgeless buck-boost converter is used for power factor correction (PFC) of low voltage high current (LVHC) multi-string light emitting diode (LED) driver. This is a design for an application in large area LED lighting with illumination modulation. A multi-mode LED dimming technique is used for lighting control. The BL buck-boost PFC converter feeds power to isolated flyback DC-DC converter. The regulated low voltage from a flyback converter is a source power to the synchronous buck converters for multi-string LED driver and forced cooling system for LED junction. The design of the inductor of BL-buck-boost PFC converter is based on discontinuous inductor current mode (DICM), which provides good PFC at low cost. A prototype is designed and tested for a LED driver. The performance of proposed HB LED driver is evaluated for a full brightness control capability. The measured harmonic parameters are found lower than range set for lighting by IEC 61000-3-2 Class C.**

***Keywords*– BL-buck-boost converter, Power Quality, DC-DC Conversion, Harmonic reduction, Lighting, Load emulator, Total harmonic distortion.**

I. INTRODUCTION

A good efficacy, long life, no filament to break, environment friendly and capability to improve further in future, are the advantages for light emitting diodes (LED) [1]. An increasing use of LED lighting and bright future to further addition create attention on power quality issues for high brightness (HB) LED drivers [2-3]. The IEC 61000-3-2 Class C harmonic norms are now recommended for LED lighting [4]. In order to improve these parameters, active power factor corrector is needed [5-6]. Normally after bridge converter, active power factor correction (PFC) converter is needed [7-10]. However, after introduction of additional PFC converter, its efficiency is reduced, however, it meets the harmonic norms. In order to improve efficiency, a low speed diode bridge converter is targeted using bridgeless PFC converter [11]. Energy storage elements like inductor, transformer or capacitors operating modes are responsible for harmonics distortion and displacement power factor. The discontinuous current mode (DCM) is capable to achieve good voltage follower with only one sensor, which is not possible with other modes of operation [4] [9-11]. Second criterion is to select converter topology for PFC stage. Normally, boost derived power conversion for voltage follower is used [5-6]. However, these power conversions have always higher output voltage relative to input, poor light load efficiency in universal input voltage operation and high dc bus capacitor requirement, which create challenges for boost converter as a universal PFC converter [6]. In order to address these issues, a buck-boost converter is introduced as a voltage follower [7].

In this work, a BL buck-boost PFC corrector for high power LED driver is used. This voltage follower scheme achieves good PF and low current THD. It helps lower DC bus capacitor requirement which is not possible in boost derived topology. Lower DC bus voltage improves converter efficiency and utilizes low cost dc bus electrolytic capacitor [8] [12]. The proposed converter design is based on DCM with power factor improvement having single output voltage feedback. The scheme is designed for projection LED of cumulative, 300W rating with nine LED strings constant current control meeting low voltage safety criterion (12V). The suitable converter architecture for such LED driver is in three stages [13-14]. The first stage is BL- buck- boost PFC converter responsible for regulated DC bus voltage with high power factor and low source current THD. The proposed scheme maintains the regulated DC bus voltage (V_{dc}) less than <5%, for entire input voltage range. It helps to maintain low ripple current for DC bus capacitor for wide input voltage variation. In this way, the life of electrolytic capacitor is enhanced for LED driver [12]. The benefits of electrolytic-less LED driver can be achieved by using such a LED driver in low cost electrolytic capacitor in such high power range [13-14]. In second stage, a constant DC bus voltage is supplies power to isolated flyback converter, which is finally a source of synchronous buck based LED driver and the LED cooling system. The forced cooling unit maintains the LED junction temperature at ambient level. In this way, there is no shift in color of LED light. The LED driver maintains linearity reason of LED characteristics supplied by LED manufacturer [15]. A commercial top switch based integrated circuit (IC) is selected for this converter. The selection of this IC, has inherent protection for high voltage cut-off, over-temperature, smooth startup and low voltage cutoff [9-11]. The peak current mode control scheme for this IC helps in fast dynamic response and pulse by pulse switch monitoring in low cost compared to other analog or digital IC solution [9-11]. Therefore, single IC selection reduces the discrete component complexity, board space and cost of LED driver. Normally in such power range resonant mode converter is used for higher converter efficiency but higher implementation cost and more complexity. Other disadvantages of resonant mode techniques are poor light load efficiency and universal line regulation [12-13]. In third stage, a constant current synchronous buck based LED driver is used with PWM dimming

978-1-5090-4894-6/17/$31.00 ' 2017 IEEE

features. The synchronous buck converter is also responsible for an illumination control. The selection of synchronous buck utilizes the high efficiency of buck derived topology for high current application [9-11]. The three independent synchronous buck converters are used for independent current control of RGB LED module with multiple LED strings. The commercial constant current Intersil IC is selected for this purpose .These synchronous buck converters have no reverse recovery loss and switching speed constraint for such high current range. It utilizes high switching speed for small size magnetics and relevant protection features in low cost. For the LED illumination control, a multi-mode dimming technique is used, which is an efficient technique available in the literature [9-11].

II. BRIDGELESS BUCK BOOST PFC CONVERTER OPERATION

Fig.1 shows proposed power converter. It is an integration of two switches (S_{w1}, S_{w2}), two inductors (I_{L1}, I_{L2}) and two diodes (D_3, D_4), which are known as two buck- boost cells. The switching cycle of proposed PFC converter is divided into two sections corresponding to its operation for a complete line cycle and active switch switching modes. Fig. 2 shows operating modes in first and second half AC line of total six cycles. The switching states and waveforms are shown in Fig.3.

A. Supply Voltage Line Cycle Operation

There are two active switches S_{w1} and S_{w2} operations are responsible for BL configuration. In positive half AC cycle, S_{w1}, is operational and S_{w2} is inactive. The switch operation is opposite in negative half AC cycle. Thus, switch S_{w1}, inductor L_{i1} and diode D_1 are in state of conduction in positive half cycle as shown in Figs.2 (a-c). Similarly, switch S_{w2}, inductor L_{i2} and diode D_2 are active in negative AC half cycle as shown in Figs.2 (d-f).Thus there are the three modes of operation for an AC cycle in proposed PFC converter. The DICM operation of the currents of the inductors (L_{i1} and L_{i2}) in a complete switching cycle is shown in Fig. 3.

B. Switching Cycle Operation

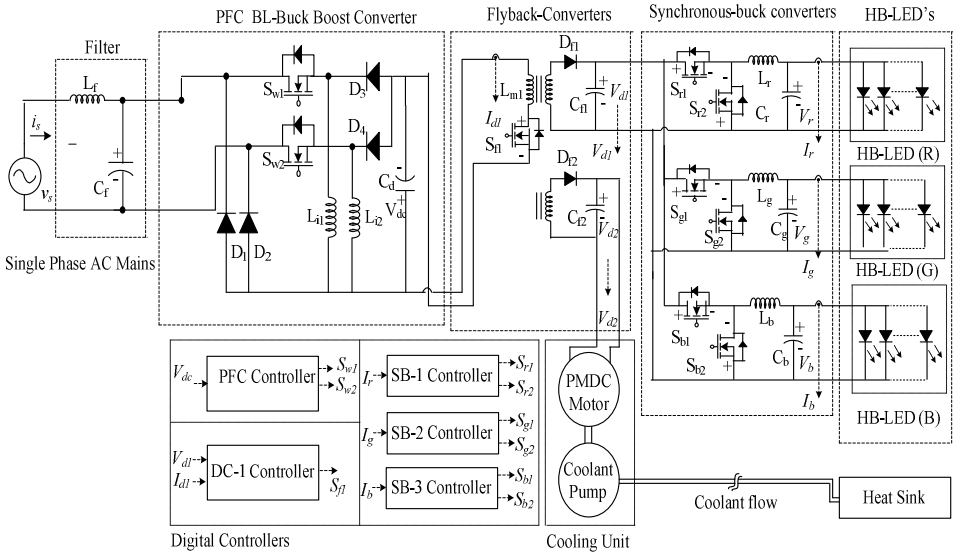
The switching states operating modes are as in positive half cycle.

Active Switch (S_{w1}) ON (Mode I): The input inductor (L_{i1}) starts charging. The diode (D_3) is reversed biased and the capacitor (C_d) supplies the required power to the downstream converter. Fig. 2(a) shows the components active states.

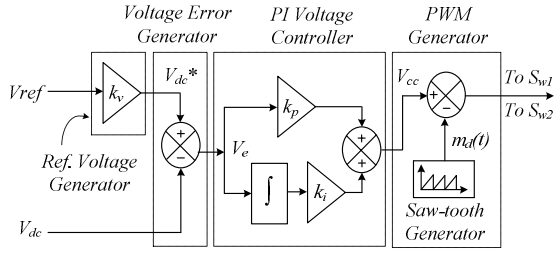
Active Switch (S_{w1}) OFF (Mode II): In Fig. 2(b), the input inductor (L_{i1}) starts discharging via diode (D_3). The DC bus capacitor (C_d) stores energy in this interval and a DC bus capacitor (C_d) charges in this mode of operation as shown in Fig. 3(b).

Active Switch (S_{w1}) still OFF (Mode III): In this interval (Fig. 2(c)), input inductor (L_{i1}) is fully discharged and the bulk capacitor (C_d) fulfills the power requirement.

Figs.2 (d)-(f) show the operating state for the negative half period in same way.



(a) Block diagram



(b) PFC control system

Fig. 1. Proposed PFC based BL-buck boost LED driver.

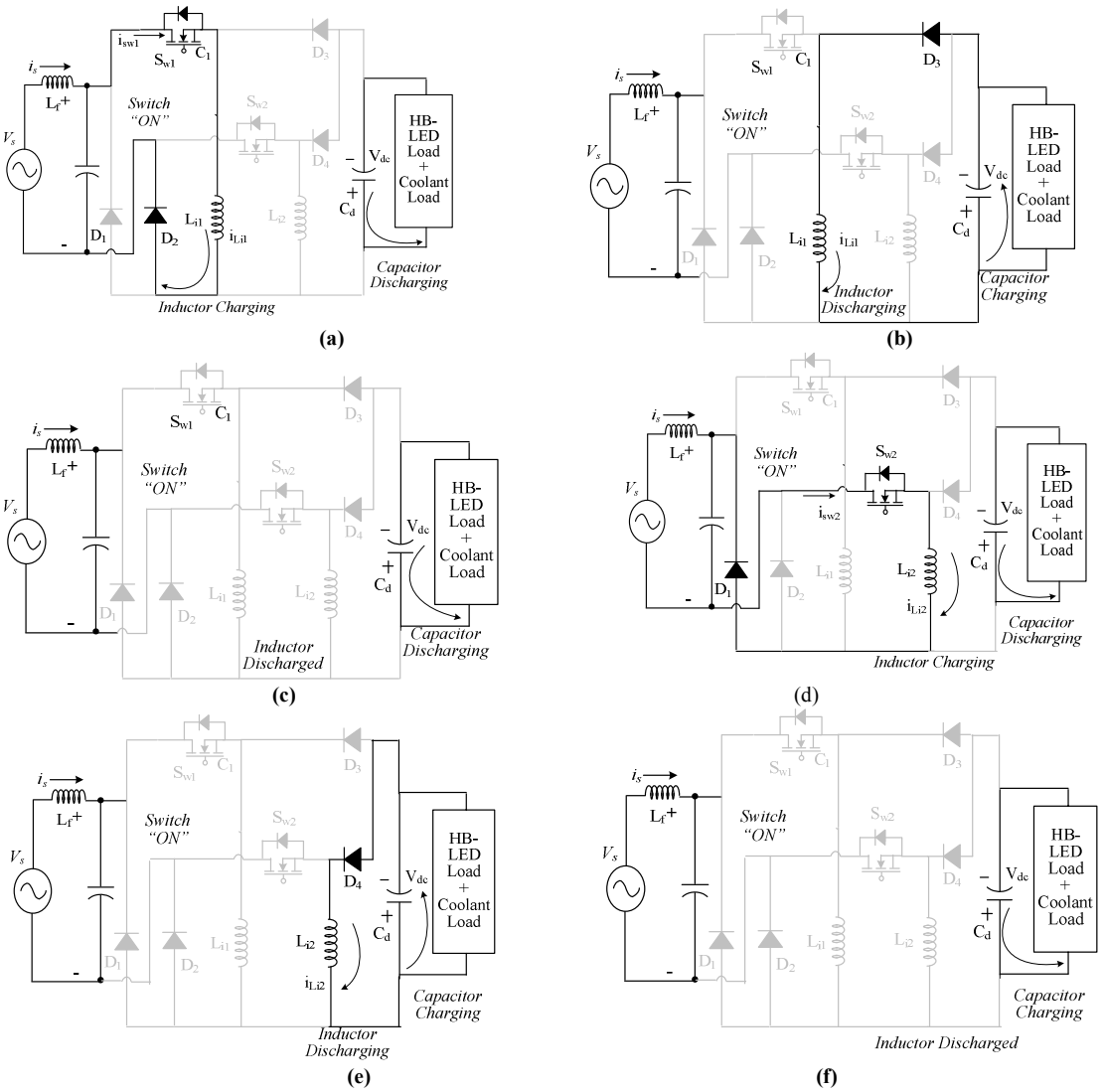


Fig. 2. Operating modes of a BL-buck boost for (a-c) first half cycle and (d-f) second half cycle of input voltage

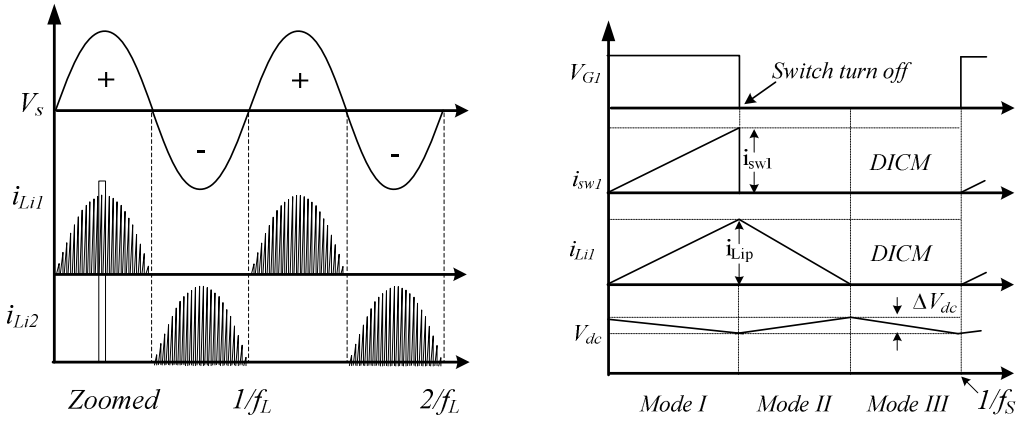


Fig. 3. Waveforms of BL-buck-boost during (a) complete cycle of line voltage and (b) complete switching cycle

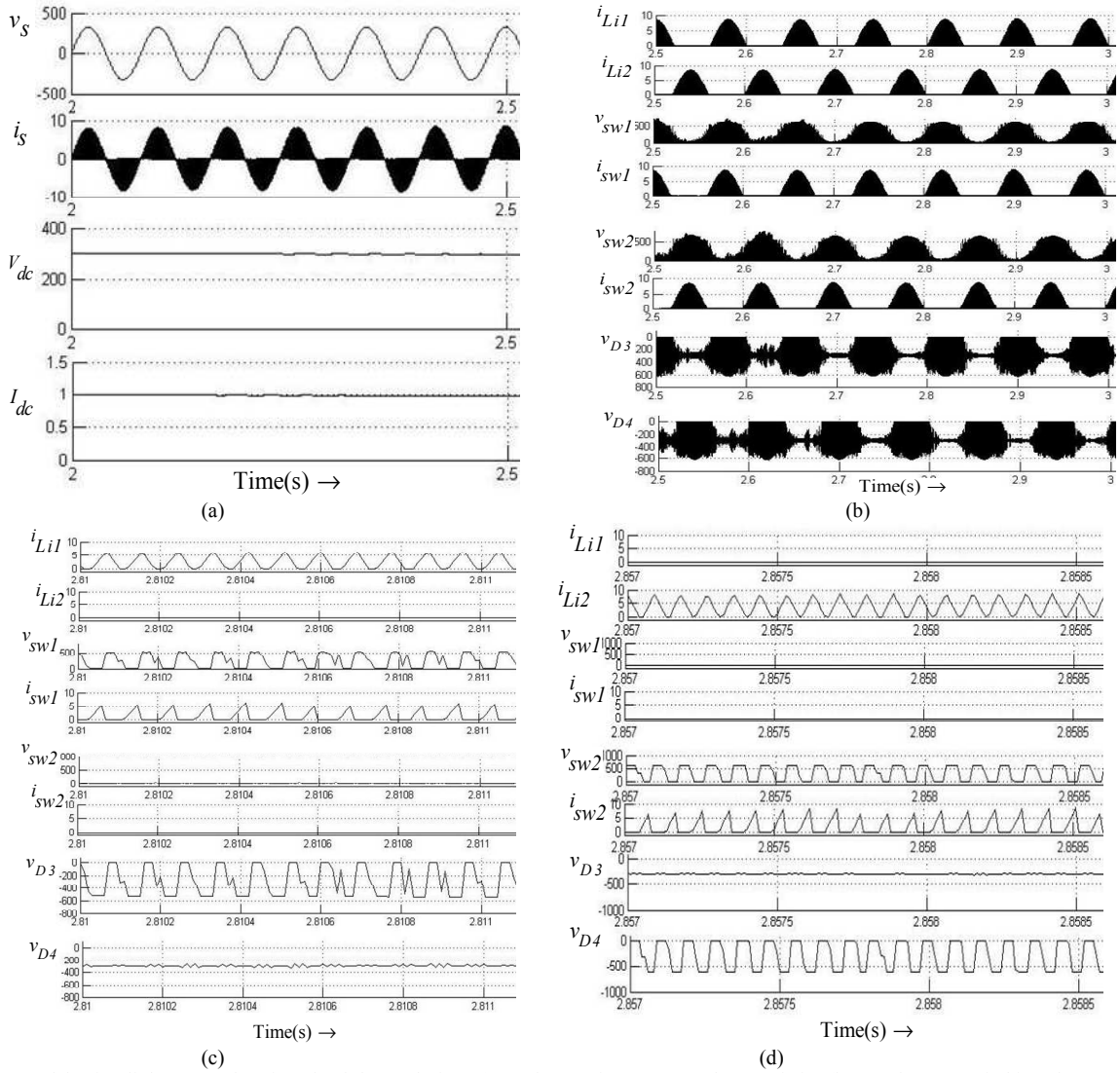


Fig. 4. Matlab-Simulink test results of BL-buck-boost during (a) steady state input output characteristics (b) Steady state switching characteristics (c) Positive cycle active and passive components switching states (d)) Negative cycle active and passive components switching states

II. Simulation Result Using MAT lab-Simulink

The proposed LED driver is simulated in commercial Matlab software. The stable condition of PFC converter is shown in Fig.4. Fig. 4(a) shows the line voltage and current are in same wave shape, which ensures good power factor. Figs. 4(c) and (d) conform the operating modes of active components discussed in section II.

III. LED Driver Prototype Design

The power converter design covers BL- buck-boost PFC, isolated flyabck, synchronous buck converter components selection and design.

A. BL- PFC Converter Design

The design of BL- PFC buck-boost converter depends on input inductors (L_{i1} and L_{i2}) currents to flow such that cycle. The designed power rating of a PFC converter is 300 W (P_{max}). The DC bus voltage is regulated to 300V with input voltage range from 90 V (V_{smin}) to 265 V (V_{smax}).

The input voltage, V_s can be written as,

$$V_S(t) = V_m \mathrm{Sin}\left(2\pi f_L t\right) = 325\,\mathrm{Sin}\left(314t\right)\mathrm{V} \quad (1)$$

Where V_m is the peak input supply (i.e. $\sqrt{2}V_S$), f_L is the supply frequency.

Now, the input voltage appearing after the bridge is as,

$$V_{in}(t) = \left|311\,\mathrm{Sin}\,(314t)\right| \quad (2)$$

Where the absolute value represented by symbol | |.

The output voltage, V_{dc} of a BL buck -boost converter is a function of duty cycle (D) as [6],

$$V_{dc} = \frac{D}{(1-D)} V_{in} \quad (3)$$

The instantaneous duty cycle, D (t) is calculated using (2) and (3) as,

$$D(t) = \frac{V_{dc}}{V_{in}(t) + V_{dc}} = \frac{V_{dc}}{\left|V_m \sin(\omega t)\right| + V_{dc}} \quad (4)$$

The source side inductors (L_{i1} and L_{i2}) are designed for accepted ripple current of η [4],

$$L_{il,i2} = \frac{V_{in}(t)(1-D(t))^2}{I_{in}(t) f_S} = \frac{R_{in}(1-D(t))^2}{\eta f_S} = \left(\frac{V_s^2}{P_i}\right)\frac{(1-D(t))^2}{\eta f_S} \quad (5)$$

Where $R_{in,}$ shows input side emulated resistance, f_s is switching frequency and P_i is the instantaneous power.

The inductor maximum ripple current is calculated at full load (300W) and lowest line voltage (V_{smin} =90V). Hence the calculated inductance value is at the lowest line supply (i.e. $V_s = \sqrt{2}\, V_{smin}$) with maximum duty cycle of 50 %, efficiency of 85% and switching frequency of 20 kHz as 793.8 µH.

The DC bulk capacitor is as follows [4], [9-11],

$$C_d = \frac{I_d}{2\omega \Delta V_{dc}} = \frac{\left(P_i / V_{dc}\right)}{2\omega \delta V_{dc}} = \frac{P_i}{2\omega \delta V_{dc}^2} \quad (6)$$

Where δ is the permissible voltage ripple in DC bus.

Now for a permissible ripple of 5% as the DC bus capacitor is 212 µF. The selected nearby capacitor value is 220 µF, 400V.

B. Design of Synchronous Buck Converter and Isolated Flyback DC-DC Converter

The isolated flyback DC-DC converter is used as a low cost isolated DC-DC converter in this power range. It provides constant DC voltage as well as isolation for multi-string LED driver. The synchronous buck converter is designed for constant current LED driver for multi-string LEDs. The detail design calculation and analysis are given in [9-11].

III. Control of Proposed Driver

There are three individual controls for proposed PFC based LED driver. These are PFC converter for control of DC bus voltage, control of flyback converter and synchronous buck converter control for achieving brightness control as follows.

A. Control of BL-Buck-Boost PFC Converter

Fig. 1(b) shows the block diagram of control system of PFC converter. The control scheme works on voltage follower scheme. It consists of reference voltage, error voltage, control voltage and PWM. A reference voltage V_{dc}* is calculated as,

$$V_{dc}^* = k_v V_{ref}^* \quad (7)$$

The error voltage compares with voltage reference (V_{dc}*) and the sensed PFC output voltage (V_{dc}), which generates an error voltage (V_e) as follows,

$$V_e(n) = V_{dc}(n)^* - V_{dc}(n) \quad (8)$$

Where 'n' shows the n^{th} sample.

The error, V_e is shown to a controller gain to generate regulated PFC output (V_{cc}) as follows,

$$V_{cc}(n) = V_{cc}(n-1) + K_p\{V_e(n) - V_e(n-1)\} + K_i V_e(n) \quad (9)$$

Where controller gains are K_p (Proportional) and K_i (Integral), respectively.

At the end PWM, generated signal for switch S_w depends on comparison of output of controller (V_{cc}) with saw-tooth signal (m_d),

$$\left\{\begin{array}{l} \text{if } m_d < V_{cc} \text{ then } S_w = \text{'ON'} \\ \text{if } m_d \geq V_{cc} \text{ then } S_w = \text{'OFF'} \end{array}\right\} \quad (10)$$

Where, S_w shows the gate pulse for active switch.

B. Control of DC-DC Converter

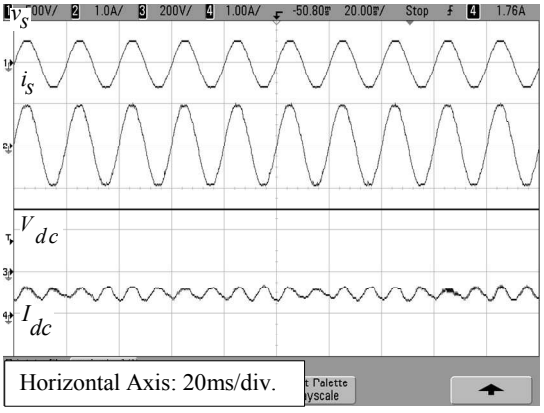
The control of isolated flyback DC-DC converter is working on peak current mode control of MOSFET. This scheme using commercial TOP switch from Power Integration [9-11]. The control equations are discussed in [9-11]. The control systems for synchronous buck converters are discussed in [9-11]. A commercial Intersil analog IC ISL8104 is used for the proposed converter.

IV. Test Results

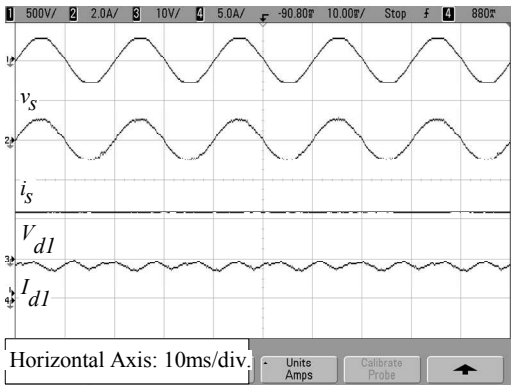
The proposed BL buck-boost PFC converter fed low voltage high current multi-string LED driver has been designed and its prototype is developed. Test results have been captured for universal input voltage with dimming. A commercial digital signal processor (DSP) (TI-TMS320F2812) is used for the development. The flyback DC-DC converter is designed for regulated DC voltage requirement of synchronous buck based LED driver. The below sections are discussing for test results:

A. Steady State Performance

The steady state performance of LED driver at full load and 50% LED load, is shown in Fig.5. Fig. 5 (a) shows its operation as PFC converter. Fig. 5(b) shows the performance of flyback converter, which is supplying power to the LED load. Figs.6 (a) and (b) show the steady state test results at 50% of LED brightness. As shown in these figures, the power converters are stable at all loading and line conditions. The input current (i_s) and input voltage (v_s) wave shape are matching, which conforms good power factor and low THD.

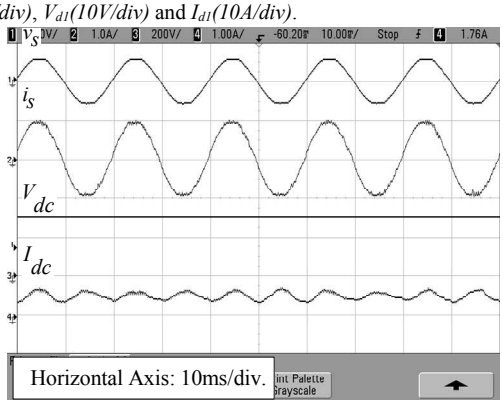


(a)

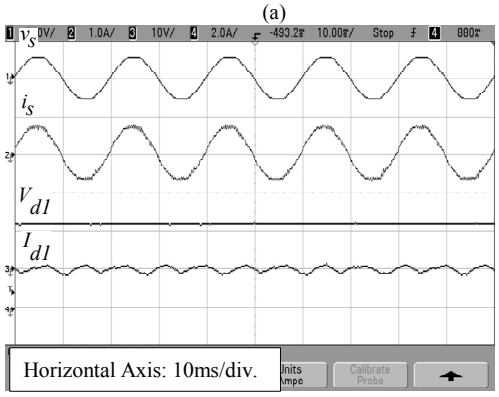


(b)

Fig. 5. Steady state performance at full load (a) V_s*(500V/div)*, i_s*(1A/div.)*, V_{dc}*(200V/div)* and I_{dc} (2A/div) and (b) *Vs (500V/div)*, i_s*(2A/div)*, V_{d1}*(10V/div)* and I_{d1}*(10A/div)*.



(a)



(b)

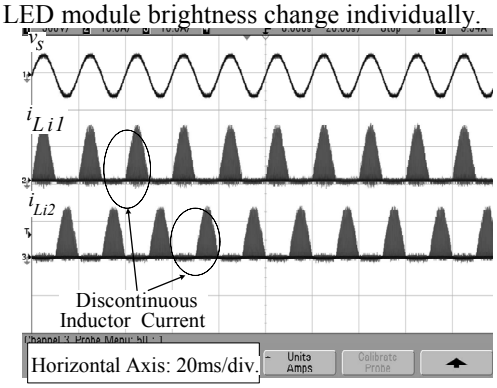
Fig. 6. Steady state performance at 50% load (a) V_s*(500V/div)*, i_s*(0.5A/div.)*, V_{dc}*(200V/div)* and I_{dc} (1A/div) (b) *Vs (500V/div)*, i_s*(0.5A/div)*, V_{d1}*(10V/div)* and I_{d1}*(5A/div)*.

B. Buck-Boost Switching Operation and Switching Stress

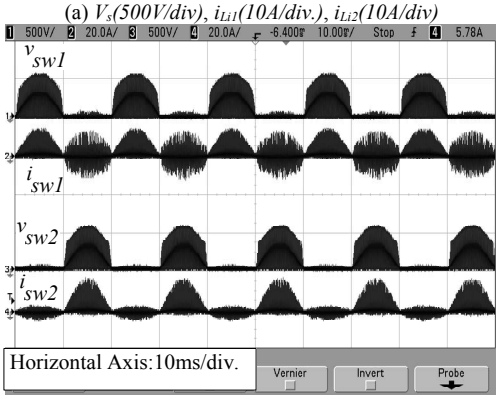
Fig.7 shows the inductor currents (i_{Li1}, i_{Li2}) of the PFC based BL buck-boost converter operating in DICM. Test results clearly indicate the operating modes of PFC converter. Fig. 7 (b) shows the switch voltages (v_{sw1}, v_{sw2}) and switch currents (i_{sw1}, i_{sw2}) of the PFC converter with supply voltage (v_s) in a complete line cycle. Moreover, the extended waveforms of voltage (v_{sw}) and current (i_{sw}) of the active switch of PFC converter are shown in Fig. 7(c). Normally one switch is inactive in one AC half line cycle. So, both switches stress shown in Fig. 7(c) is indicative only. As shown in Fig.7 (c), a maximum voltage and current stress of the order of 570 V and 12A are observed, which is acceptable for this power converter operating in discontinuous conduction.

C. Transient Behavior of the LED Driver

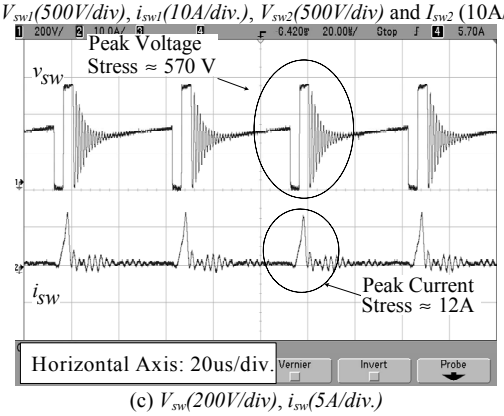
For an LED diver, responses are recorded at load changes (dimming) and source fluctuations. Fig. 8(a) shows LED intensity variation from half to full load. As shown in these figures, the DC bus voltage is maintained constant at their respective reference values. Moreover, the response for input voltage variation from 265 V to 180V is shown in Fig.8 (b) at full load. The three step change in current in Fig.8 (a) shows the red, green and blue LED module brightness change individually.



(a) V_s*(500V/div)*, i_{Li1}*(10A/div.)*, i_{Li2}*(10A/div)*

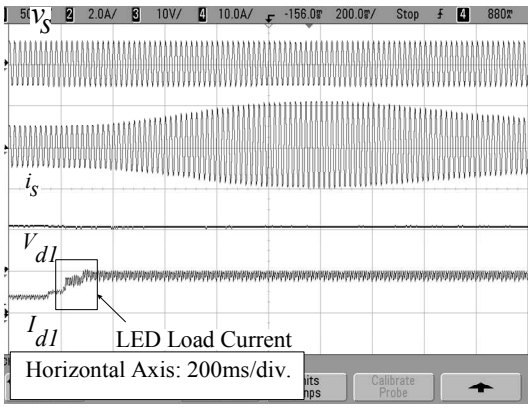


(b) V_{sw1}*(500V/div)*, i_{sw1}*(10A/div.)*, V_{sw2}*(500V/div)* and I_{sw2} (10A/div)

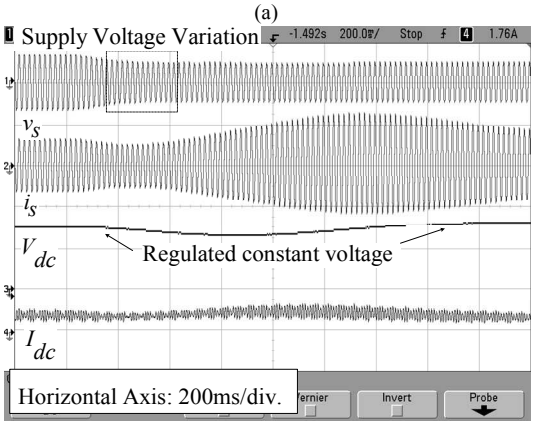


(c) V_{sw}*(200V/div)*, i_{sw}*(5A/div.)*

Fig. 7. Test results showing (a) input voltage (v_s) and intermediate inductor currents (i_{L1}) and (i_{L2}) (b) switch voltages (V_{sw1}), (V_{sw2}), switches currents (i_{sw1}), (i_{sw2}) (b) its extended waveforms at full load.



(a)

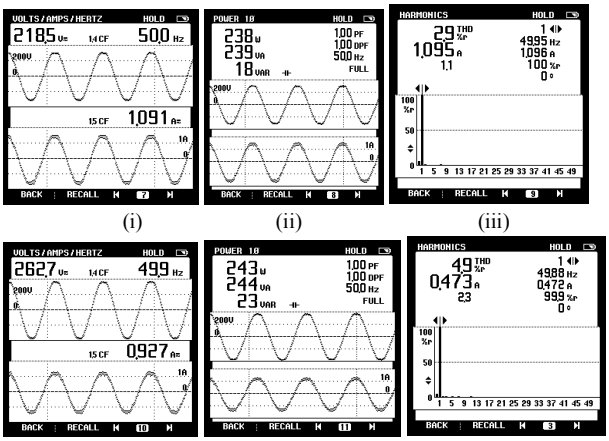


(b)

Fig. 8. Dynamic performance for LED driver for (a) load variation *Vs (500V/div)*, i_s*(2A/div)*, V_{d1}*(10V/div)* and I_{d1}*(20A/div)* (b) input voltage variations V_s*(500V/div)*, i_s*(2A/div.)*, V_{dc}*(200V/div)* and I_{dc} (2A/div)

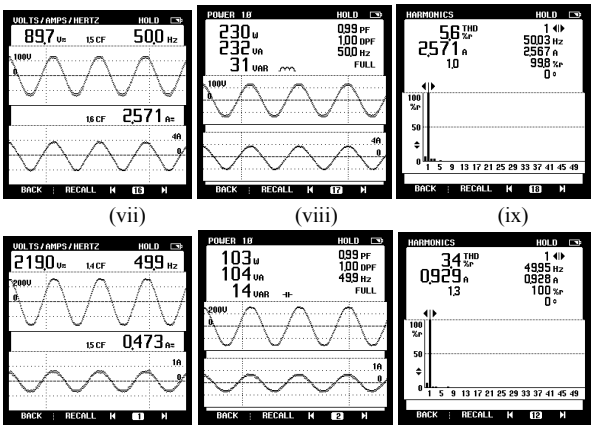
D. PF and THD Measurement

The power quality parameters like power factor and THD of power supply are measured on a power analyzer. The measured values are for all LED loade.Figs.9 (i)-(iii) show its performance at minimum supply voltage 90 V. Figs.9 (iv)-(v) show its performance at nominal supply voltage 220V. Figs.8 (vi)-(viii) show its performance at 265V. Moreover, Figs. 8 (ix-xii) show the power quality indices at 20% brightness. These indices are within the desirable limits of IEC 61000-3-2 Class C.



(i) (ii) (iii)

(iv) (v) (vi)



(vii) (viii) (ix)

(x) (xi) (xii)

Fig. 9. Power quality parameters of LED driver at full load with input voltage (v_s) as (i-ii-iii) 220 V (iv-v-vi) 265V (vii-viii-ix) 90V (x-xi-xii) 220V at 20% LED current

IV. CONCLUSION

A LED driver fed by buck-boost BL-PFC converter has been developed for LED lighting application. The proposed converter is supplying power to the downstream converter and cooling unit. The proposed driver is efficient and capable to control LED brightness for large screen projection, illumination or display application. The proposed LED driver performance has been verified at steady and dynamic load and line conditions. A good power quality performance has been observed at various line and load with permissible limit of IEC1000-3-2 Class C. The proposed scheme is expected to be a possible alternative LED driver with brightness control.

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