Performance Analysis of Coupled Inductor Based Ripple Free Boost PFC AC-DC LED Driver

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***Abstract*—Power factor correction (PFC) and the elimination of second harmonic ripple without using an electrolytic capacitor (EC) are the key factors for an AC-DC Light Emitting Diode (LED) driver. The ECs are used to diminish the pulsating current with double the supply frequency at the output which reduces the life span of the LED driver. In this paper, a Boost converter with a coupled Inductor Bi-directional converter (CIBDC) configuration is proposed. This configuration consists of a Boost PFC converter and CIBDC for replacing the short life span ECs with long life span film capacitors. Boost PFC is operated in discontinuous conduction mode (DCM) to obtain unity power factor and CIBDC diverts the ac component of the Boost PFC converter and allows the dc component to the LED load. Also, by using coupled inductor zero voltage switching (ZVS) is achieved for the power switches to reduce the switching losses. Hence, the proposed configuration has advantages of near unity power factor, reduced switching losses for improved efficiency, elimination of ECs, and low output current ripple. A 100 W AC-DC LED driver configuration is validated using PSIM software.**

***Index Terms*—AC-DC LED driver, Boost PFC Converter, Discontinuous Conduction mode (DCM), Coupled Inductor Bi-directional Converter (CIBDC), Zero Voltage switching (ZVS).**

I. Introduction

Artificial light plays a crucial role in every aspect of human life. In developing countries, lighting energy consumption is approximately 30% of the total energy production. Currently, the electric light sources enhanced to the next level of revolution by the introduction of Solid-State Lighting (SSL). Light Emitting Diodes (LED), a type of SSL, has outshone many existing lighting technologies in terms of high energy efficacy, reliability, long lifetime, pollution-free and low maintenance. The world lighting market is forecasted to grow around 15% annually because of growing awareness about environment-friendly products and energy efficiency is the key mitigation strategy for carbon emissions [1]. Grid-connected LED drivers utilize single-phase ac source as input which requires Power factor Correction (PFC) to meet the harmonic standards of IEC61000-3-2 [2]. The inherent behavior of the LED allows only unidirectional current to go through it requires an AC-DC conversion to achieve nearly unity power factor (UPF) and ripple free output power.

In literature study the LED drivers are classified based on the power stages like single-stage, integrated two-stage and multi-stage. Single Stage LED driver topologies achieves either desired power factor or ripple free output with compact size but unable to remove electrolytic capacitor with the combined performance [3]. To overcome the drawbacks of single-stage LED drivers, the PFC stage and DC-DC stage are merged to form an integrated single-stage topology. Apart from the PFC and ripple free output, few topologies implemented soft switching by using extra snubber circuits or by using resonant converters to obtain high efficiency [4]. Few topologies are stepped ahead and implemented the soft switching by means of the phase shift without using extra snubber circuits [5]. These topologies have an advantage of high PF, higher efficiency by means of soft switching, less component count, compact size and less weight. But they suffer from demerits like usage of a bulky capacitor, the high voltage stress on the devices due to the integrated operation on the single device and losing the capability of galvanic isolation. For medium power applications multi-stage converter topologies can be preferred which has a dedicated stage for PFC and ripple free output. In order to remove the electrolytic capacitor at the output an LC filter is implemented in the input to attenuate the second harmonic ripple [6], but it suffers with the drawback of large converter size because the LC filter operates at low frequency. Few authors proposed active filters [7] as the second stage to absorb the harmonics but have a limitation of high inductor current stresses. L.Gu et. al have proposed two approaches to eliminate electrolytic capacitor, first is by intentionally increasing the capacitor voltage to reduce the capacitance of the storage capacitor and second is by injecting third harmonics into the supply current [8]. These approaches serve the need but have a drawback of unstable operation and high voltage stresses due to large voltage ripple in the earlier approach and in the later approach the input PF has to be sacrificed because of injection of harmonics. In [9], [10] the second stage which is a bi-directional converter (BDC) connected in shunt with the PFC converter to divert the ac component and allows only dc component to the load. The BDC is operated at higher frequency but doesn't provide any soft switching to the power devices which reduces the overall efficiency of the converter. This paper proposes a Boost PFC integrated BDC converter with soft switching by using a coupled inductor. The proposed configuration has advantages of near unity power

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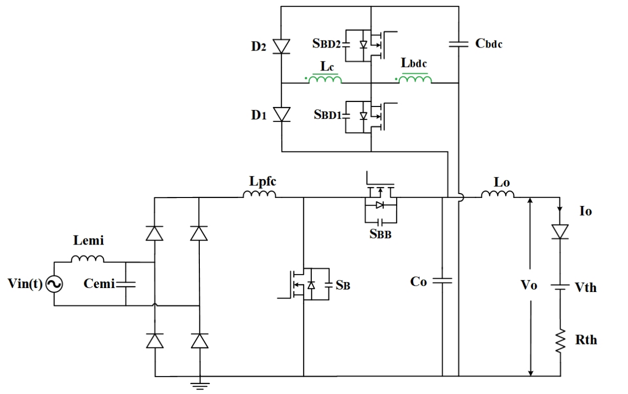


Fig. 1. Proposed Boost PFC Converter with Coupled Inductor Buck-Boost BDC.

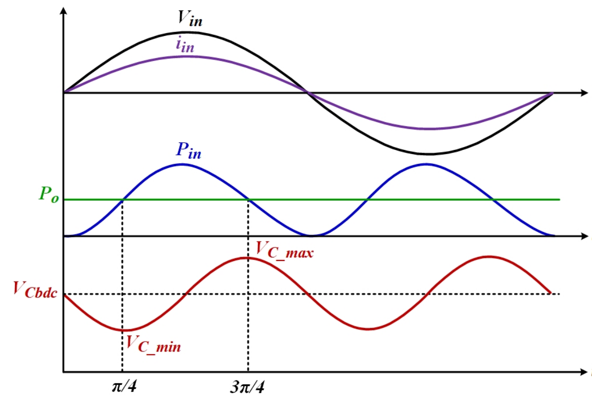


Fig. 3. Key Waveforms of Coupled Inductor Buck-Boost BDC Converter

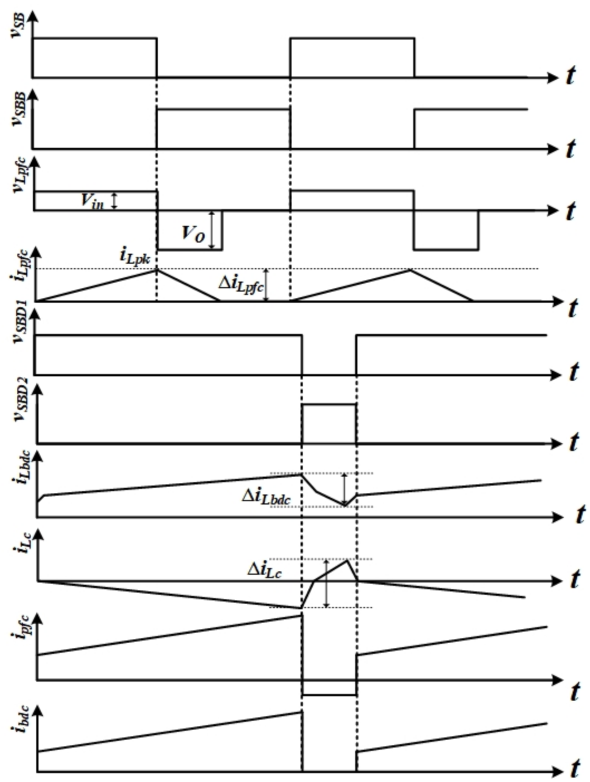


Fig. 2. Theoretical Waveforms of Boost PFC and CIBDC Converter.

factor, reduced switching losses, elimination of ECs and low output current ripple.

II. OPERATION OF PROPOSED LED DRIVER

A. Description

The proposed PFC converter configuration shown in Fig. 1 consists of a diode bridge rectifier with a Boost PFC converter which is designed to operate at discontinuous mode (DCM) to provide inherent near UPF with low current THD. The Boost PFC converter is integrated with a coupled inductor BDC (CIBDC) converter to eliminate the second harmonic (100 Hz) ripple at the output, which further helps in replacing electrolytic capacitor with a film capacitor so that the life span of the converter increases. Fig. 2 and Fig. 3 shows the theoretical waveforms of the proposed LED driver. The power switches S_B and S_{BB} are turned ON consecutively, so that the inductor L_{pfc} gets charged during S_B is turned ON, while the capacitor (C_0) will supply power to the output load. When S_{BB} is turned ON, the charged inductor L_{pfc} along with the source, will charge the C_0 and supply power to the output load. CIBDC in the proposed driver eliminates the bulky ECs by replacing it with the film capacitors. CIBDC consists of two power switches (S_{BD1} & S_{BD2}), two diodes (D_1 & D_2), coupled inductor (L_{bdc}, L_c) and a film capacitor (C_{bdc}). The auxiliary circuit formed by L_c, D_1 & D_2 creates soft switching for the power switches S_{BD1} & S_{BD2}. The operation of CIBDC categorized into two conditions, one is $P_{in} > P_0$ and second is $P_{in} < P_0$. In both the conditions the principle of operation is similar but the direction of the current reverses in the main inductor (L_{bdc}) of the coupled inductor.

The instantaneous input supply voltage $v_{in}(t)$ and supply current $i_{in}(t)$ are given by

$$v_{in}(t) = V_m sin\omega t \tag{1}$$

$$i_{in}(t) = I_m sin\omega t \tag{2}$$

Hence the instantaneous power is given by

$$P_{in}(t) = v_{in}(t)i_{in}(t) = \frac{V_m I_m}{2} - \frac{V_m I_m}{2}cos(2\omega t) \tag{3}$$

Considering the converter as ideal (i.e. $P_0 = P_{in}$) the power in Eq. (3) appears across the output capacitor C_0 which consists of both ac component and dc component as shown in Fig. 3. The CIBDC absorbs the ac component and allows only dc component to the load.

In order to reduce the capacitance value, the ripple across the capacitor is intentionally increased and calculated the value by using the Eq.(4)

$$V_{Cbdc} = \frac{V_{Cmin} + \sqrt{\frac{2P_0}{\omega C_{bdc}} + V_{Cmin}^2}}{2} \tag{4}$$

Coupled Inductor is designed based on the following Eq.(5)

$$\begin{aligned} M &= k\sqrt{L_{bdc}L_c} \\ V_{lbdc} &= L_{bdc}\frac{di_{lbdc}}{dt} - M\frac{di_{lc}}{dt} \\ V_{lc} &= -M\frac{di_{lbdc}}{dt} + L_c\frac{di_{lc}}{dt} \end{aligned} \tag{5}$$

The function of a coupled inductor in the buck-boost has to follow the double frequency current ripple and also should maintain a small ripple. Hence it should be a trade-off between the 100 Hz current tracking speed and the ripple. For a 50 Hz supply frequency, the inductor should follow 100 Hz ripple which is much slower. Hence high switching frequency of 163 kHz is chosen, which can satisfactorily track the double frequency current ripple and also reduces the size of the inductor with less ripple. The switching frequencies of flyback and coupled inductor BDC are independent of each other and there is no relationship in choosing the switching frequencies between both the converters.

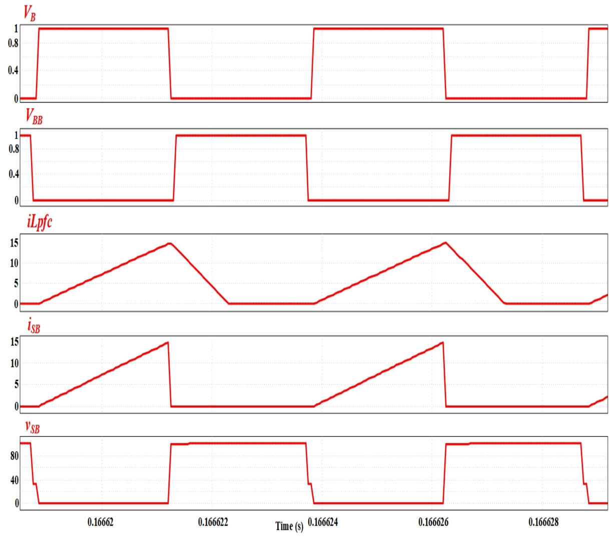
TABLE I
SPECIFICATIONS OF PROPOSED LED DRIVER

S.No	Parameter Description	Value
1	Input Voltage (V_{peak})	35V to 70V
2	Output Voltage (V_0)	100 V
3	Output Power (P_0)	100 W
4	Output Capacitor (C_0)	5 μF
5	Output Inductor (L_0)	0.5 mH
6	Switching Frequency	200 kHz
7	Main Inductor (L_{bdc})	1.3 mH
8	Auxiliary Inductor (L_C)	0.3 mH
9	Mutual Inductance	0.5 mH
10	BDC Capacitance (C_b)	30 μF
11	BDC Switching Frequency	163 kHz

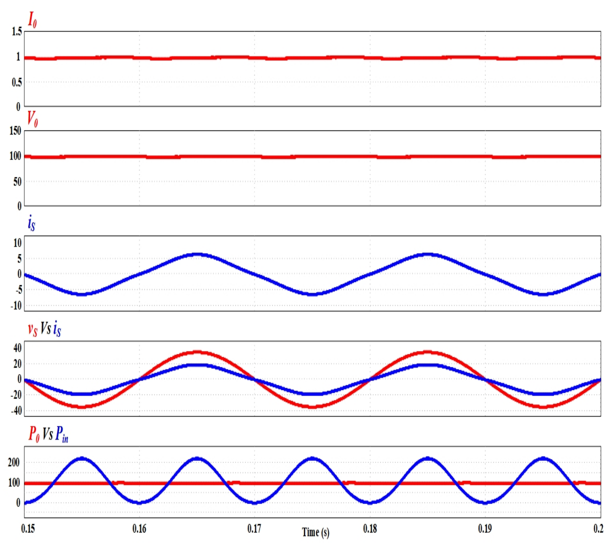
III. ANALYSIS OF SIMULATION RESULTS

The proposed converter is designed for an output power of 100 W with an output voltage of 100 V. In the proposed topology Boost converter is operated in Discontinuous Conduction Mode (DCM) for the Power Factor Correction,hence the proposed converter is operated at the reduced input voltage.

Table I provides specifications of the proposed converter. Table I and Table II gives a comparison between the proposed converter with different Boost PFC topologies. Fig. 4 & 5 illustrates the simulation results of the proposed LED driver. Fig. 4a & 4b shows the simulation waveforms of Boost PFC converter's V_B, V_{BB}, i_{Lpfc}, i_{SB}, v_{SB}, I_o, V_o, i_s, v_s & i_s and P_o & P_{in}.



(a)



(b)

Fig. 4. Simulation waveforms of Boost PFC converter: (a) V_B, V_{BB}, i_{Lpfc}, i_{SB}, v_{SB} (b) I_o, V_o, i_s, v_s & i_s and P_o & P_{in}.

From Fig. 4 it is evident that the current i_{Lpfc} is discontinuous for DCM operation, also, source draws a sinusoidal current and maintains a PF of 0.99. Fig. 5 depicts the CIBDC converter waveforms V_{SBD1}, V_{SBD2}, i_{Lbdc}, i_{SBD1} and i_{SBD2}. The negative current through the power switches represents the conduction of switch diode which provides ZVS turn-ON condition. This is due to the auxiliary circuit formed by the coupled inductor and diodes in the CIBDC converter. The main inductor of the CIBDC absorbs the second harmonic ripple and allows only dc component to provide a flicker free operation of the LED. Hence, the proposed configuration claims the advantages of near unity power factor, reduced switching losses for improved efficiency, replacing ECs with film capacitors and low output current ripple.

In Table II, the percentage of current ripple indicates the

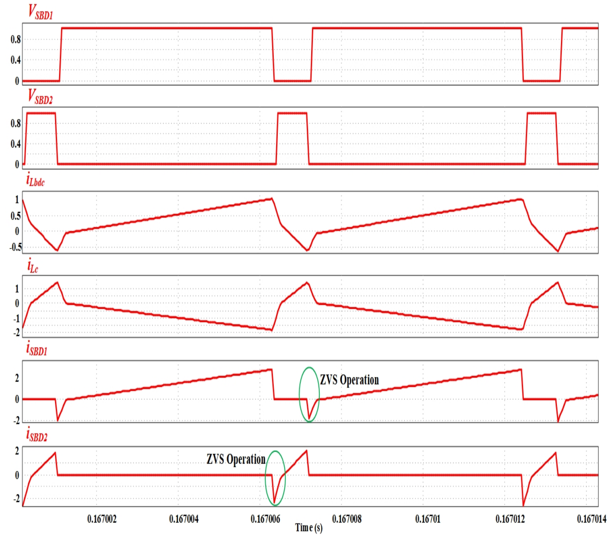


Fig. 5. Simulation waveforms of ripple assimilation CIBDC with ZVS operation of switches S_{BD1} & S_{BD2}.

TABLE II
PERFORMANCE COMPARISON OF PROPOSED LED DRIVER

Parameters	Boost PFC with Film Capacitor	Boost PFC with Electrolytic Capacitor	Boost PFC with Inductor BDC	Boost PFC with CIBDC
Capacitor	5 μF	1000 μF	5 μF	C_0= 5 μF C_b=30 μF
Power Factor	0.99	0.99	0.99	0.99
% Current Ripple	189%	11.72%	99%	3.30%
Efficiency	99.99%	99.92%	94.54%	96.11%

flickering of LEDs at double the supply frequency, which is undesirable for the LED applications. It should be as less as possible to provide a constant DC current to the LEDs. In the proposed converter, the percentage of current ripple is much less than the other topologies, which provides a constant DC current to LEDs and also reduces the flickering effect of the LEDs.

IV. CONCLUSION

In this paper, a simulation study of 100 W Coupled inductor based ripple free Boost PFC configuration for LED drivers is presented, which eliminates the bulky electrolytic capacitor and replaces it with a film capacitor. From the simulation results, it is validated that soft switching is achieved for the CIBDC power switches using coupled inductors that improve the efficiency and also, the ripple across the capacitor is reduced to 3.3%. In addition, PF of 0.99 is obtained by the DCM operation of the Boost converter. The simulation study illustrates that the proposed configuration provides significant reduction in output ripple voltage and current, soft switching to the power switches and increases the life span of the LED driver by replacing ECs with film capacitors.

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