International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 7, No. 3, September 2016, pp. 880~891
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v7.i3.pp880-891

A Novel Power Factor Correction Modified Bridge Less-CUK Converter for LED Lamp Applications

Saravanan D[1], Gopinath M[2]
[1] Department of Electrical and Electronics Engineering, St. Peter's University, Chennai, Tamilnadu, India
[2] Deparment of EEE, Dr.N.G.P. Institute of Technology, Coimbatore, Tamilnadu, India

Article Info

Article history:

Received Nov 12, 2015
Revised Mar 30, 2016
Accepted May 1, 2016

Keyword:

Modified BL cuk converter (MBL-CUK)
PFC bridgeless cuk converter
Power utility devices
Power factor correction (PFC) converter

ABSTRACT

In recent decades, several research works have been focused on the efficient Power Factor Correction (PFC) converter design in to meet the power supply efficiency. Conventional PFC cuk converter widely uses the full bridge rectifier which had resulted in overall increase of converter losses and inefficiency. This paper is intended to develop a novel PFC Bridgeless cuk converter for LED lamp applications. In this work, the limitations of the conventional PFC Cuk converter are resolved. The major contributions of the proposed work include the minimization in the number of conduction devices and minimization of the power utility devices which in turn resulted in minimal losses and better efficiency. Moreover, the proposed converter works in DCM which requires only one voltage sensor which results in reduced cost. The proposed Modified BL Cuk converter (MBL-CUK) for LED lamp is simulated in MATLAB and the corresponding results show the better power quality indices such as power factor and Total Harmonic Distortion.

Corresponding Author:

Saravanan D,
Department of Electrical and Electronics Engineering,
St.Peter's University, Chennai, Tamilnadu, India.
Email: saravanandrs16@gmail.com

1. INTRODUCTION

The usage of Light Emitting Diode (LED) lamp in household and industrial appliances is finding manifold increase in its application due to its features like being Energy efficient (energy efficiency of 80%-90% in comparison with age-old lighting techniques and traditional light bulbs), Long Lifetime (This offers 11 years of continuous operation, or 22 years of 50% operation), environment friendly (LED's have no mercury or other substances that are hazardous), Rugged (It is made of solid material with no filament or tube or bulb that breaks), Instant Lighting (LED lights brighten up immediately after powering on, that renders huge benefits for infrastructure projects like e.g. traffic and signal lights), Being Operational in Extremely Cold or Hot Temperatures, and Low operating Voltage (A low-voltage dc power supply is enough for LED illumination e.g. 6V, 12V etc.) [1], [2].

A LED lamp Power supplies with active power factor correction (PFC) techniques are required for satisfying harmonic regulations and standards, like the IEC 61000-3-2. The traditional scheme of a LED lamp power supplies that is fed by a diode bridge rectifier (DBR) and a high value of filter capacitor takes a non-sinusoidal current, from ac mains that is rich in harmonics in such a way that the Total Harmonic Distortion (THD) of supply current is as high, resulting in poor power factor that is as low as 0.8. These kinds of power quality indices cannot adhere with the international power quality standards like the IEC 61000-3-2 [3], [4]. Therefore, single-phase efficient PFC converters are necessary for attaining a unity power factor at ac mains [5], [6].

In order to increase the power supply efficiency, significant research efforts have been aimed towards the design of bridgeless PFC converter circuits, where the number of semiconductors producing losses is minimized by essentially removing the full bridge input diode rectifier. In the recent times, multiple bridgeless PFC rectifiers have been proposed for the purpose of improving the rectifier power density and/or minimize noise emissions through soft-switching techniques [7]-[12]. Many of the bridgeless PFC rectifiers use a boost converter at their front end. But, the bridgeless boost rectifier [13]-[16] has the same critical practical setbacks just as the traditional boost converter like the dc output voltage is higher than the peak input voltage, absence of galvanic isolation, and high start-up inrush currents. Hence, for the applications involving low-output voltage, as in telecommunication or computer field, an extra converter or an isolation transformer is necessary for stepping-down the voltage.

In an effort to get over these disadvantages, different bridgeless topologies, that are appropriate for step-up/step-down applications have been newly introduced recently in [17]-[20]. But, the topology proposed in [17] is still affected by the fact of having three semiconductors in the current conduction path during each switching cycle. In [18]-[20], a bridgeless PFC rectifier which is based on the single ended primary-inductance converter (SEPIC) topology is introduced.

Just as the boost converter, the SEPIC converter has the drawback of discontinuous output current leading to a comparatively high output ripple. The CUK converter yields many benefits in PFC applications, like the easy implementation of transformer isolation, natural protection against inrush current that occurs at start-up or overload current, lower input current ripple, and less electromagnetic interference (EMI) related to the discontinuous conduction mode (DCM) topology [21], [22].

Choice of operating mode of the PFC converter is a kind of compromise between the permitted stresses on PFC switch and expenditure of the overall system. A PFC converter is designed to operate in the two different modes of operation such as Continuous conduction mode (CCM) and discontinuous conduction mode (DCM) of operation [23-24]. A voltage follower approach is one among the control techniques utilized for a PFC converter that operates in the DCM [25]. This voltage follower technique needs a single voltage sensor for regulating the dc-link voltage with a near unity PF at ac mains. Hence, voltage follower control has an edge over a current multiplier control of needing a single voltage sensor. This renders the control of voltage follower a simpler means to attain PFC and output voltage control, though at the expense of large stress on PFC converter switch. On the contrary, the current multiplier approach yields low stresses on the PFC switch, but still three sensors for PFC and output voltage control [5], [6] are necessary. Based on the design parameters, either of the approach may urge the converter to either operate in the DCM or CCM.

The main objective of this paper is to develop a novel PFC Bridgeless cuk converter for LED lamp applications. The major contributions of the proposed work include the minimization in the number of conduction devices and minimization of the power utility devices which in turn resulted in minimal losses and better efficiency.

2. CONVENTIONAL AND PROPOSED PFC SCHEME OF CUK CONVERTER FOR LED LAMP APPLICATIONS

The traditional PFC Cuk converter-based LED lamp driver that uses a current multiplier approach illustrated in Figure 1. It consists of front end Diode Bridge Rectifier (DBR), DC filter, and PFC based cuk converter. The traditional PFC Cuk converter operates in the CCM applying a current multiplier approach i.e., the current flowing in the input and output inductors (L1 and Lo), and the voltage across the intermediate capacitor (C1) stay continuous in a switching period. But it needs the sensing of two voltages (output voltage and supply voltage) and input side current for PFC operation, which is not of economic cost [26].

Furthermore, a traditional PFC scheme has lower efficiency because of considerable losses in the front end diode bridge rectifier. A traditional PFC Cuk converter is indicated in Figure 1; the current flows through two rectifier bridge diodes and the power switch (Q) during the switch ON-time, and the output diode (D0) conducts only during the switch OFF-time. Therefore, during each switching cycle, the current flows through three of the power semiconductor devices. Consequently, a considerable conduction loss, incurred by the forward voltage drop across the bridge diode, would deteriorate the converter’s effectiveness, particularly at a low line input voltage.

Figure 2 illustrates the proposed PFC (Modified Bridge Less-CUK) MBL-CUK converter-based LED lamp driver exploiting a voltage multiplier approach. It consists of front end Partially Eliminated Diode Bridge Rectifier, and PFC based MBL-CUK converter. A high frequency metal-oxide-semiconductor field-effect transistor (MOSFET) is utilized in the newly introduced MBL-CUK converter for PFC and output voltage control. This proposed converter operates in the DCM making use of a voltage follower approach i.e., the current that flows in either of the input or output inductor (Li and Lo) or the voltage across the intermediate capacitor (C1) tends to become discontinuous in a switching period. On the contrary, DCM needs a single voltage sensor for output voltage control, and intrinsic PFC is attained at the ac mains.

The new MBL-CUK converter is formed by having a connection between two dc-dc Cuk converters, one for each half-line period (positive half cycle) of the input voltage. Additionally, Figure 2 indicates that one rail of the output voltage bus is connected to the input ac line always through the slow-recovery diodes Dp and Dn. This way, the proposed topologies are not affected by the high common-mode EMI noise emission problem. Furthermore the proposed converter makes use of two powerswitches (Q1 and Q2). But still, the same control signal can control the two power switches which considerably provide simplicity to the control circuitry.

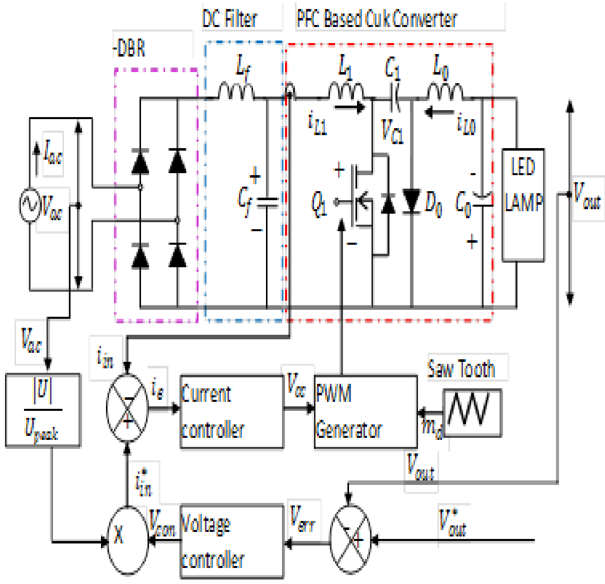


Figure 1. The traditional PFC Cuk converter-based LED lamp driver

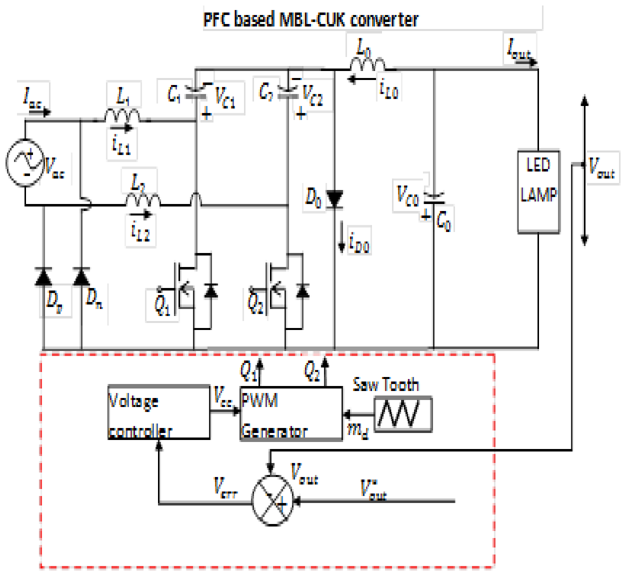


Figure 2. The proposed PFC (Modified Bridge Less-CUK) MBL-CUK converter

A short comparison between conventional and proposed cuk converter is tabulated in Table I. The comparison is conducted based on the total number of components (switch-Sw, diode-D, inductor-L, and capacitor-C) and the total number of components that are conducting during each half cycle of supply voltage. The newly introduced configuration of the MBL-CUK converter has the minimum number of components and least number of conduction devices during each half cycle of supply voltage thereby minimizing the associated conduction losses. The working principle of the novel MBL-CUK converter and the respective converter control loop is described in sections.

Table 1. Comparison between the conventional and proposed cuk converters

Particulars	Conventional cuk converter (CCM)	Proposed MBL-CUK converter (DCM)
Current conduction path when switch Q1 ON	2 slow diodes and 1 switch	1 slow diode and 1 switch
Current conduction path when switch Q1 OFF	3 diodes (2 slow and 1 fast)	2 diodes (1 slow and 1 fast)
Current conduction path in DCM	2 slow diodes	1 slow diode
Overall Component counts including DC Filter	12	11

3. OPERATING PRINCIPLE OF MBL-CUK CONVERTER

The newly introduced MBL-CUK converter is designed for operation in DCM in such a way that current in inductor L1becomes discontinuous for a switching period. Figure 3(a)-(f) illustrates different modes of operation during a complete switching period for the respective positive and negative half-cycles of the supply voltage. Figure 4 depicts the associated waveforms during the three modes of operations.

3.1. Operation during positive half-cycles of supply voltage

Mode 0: As indicated in Figure 3(a), when switch Q1 is turned on, the input side inductor L1 begins charging, and current iL1 increases, while the intermediate capacitor C1 commences to discharge by means of switch Q1 in order to charge the output capacitor C0. Hence, the voltage across intermediate capacitor VC1 decreases, on the other hand, the output voltage VL increases.

Mode 1: When switch Q1 is turned off, the energy that is stored in input inductor L1 starts discharging to the intermediate capacitor C1via diode D0 and Dp, as illustrated in Figure 3(b). The current iL1 decreases, when the intermediate capacitor voltage continues to increase in magnitude in this mode of operation. In addition, output side inductor L0 begins discharging, and output voltage VL increases, as illustrated in Figure 3(b).

Mode 2: This mode is the DCM of operation as the current in input inductor L1 becomes zero, the output side inductor L0 starts discharging, and output capacitor voltage VC0 increases, as indicated in Figure 3(c) while the output capacitor C0 supplies the necessary energy to the load.

3.2. Operation during negative half-cycles of supply voltage

Similar behavior of the converter is observed for the other negative half-cycle of the supply voltage. An input inductor L2, switch Q2, an intermediate capacitor C2, diodes Dn and D0, output side inductor L0 and output capacitor C0 conduct in a similar manner, only there is a difference in the current flow direction as illustrated in Figure 3(d)-(f).

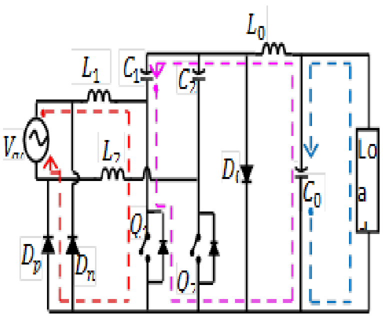


Figure 3(a). Mode 0 operation during positive half-cycles of the supply voltage

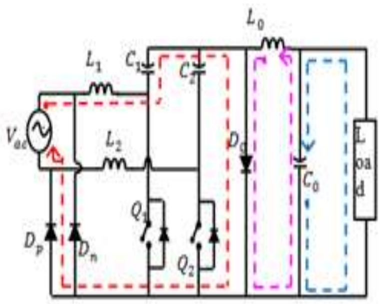


Figure 3(b). Mode 1 operation during positive half-cycles of the supply voltage

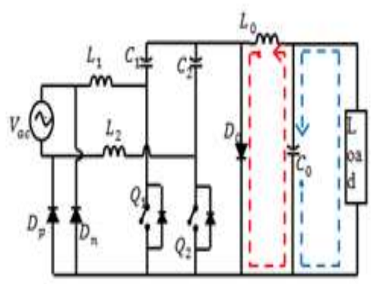
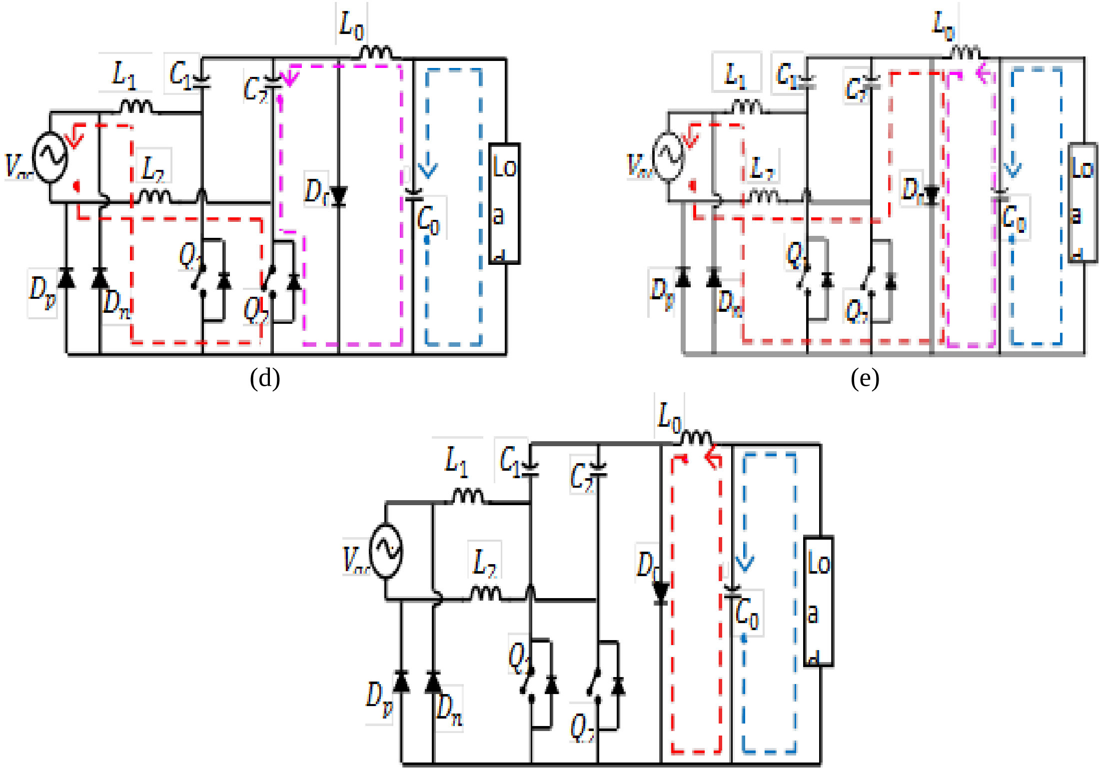


Figure 3(c). Mode 2 operation during a complete switching period for the positive half-cycles of the supply voltage



(d) (e) (f)

Figure 3(d)-(f). Modes of operation during negative half-cycles of the supply voltage

4. DESIGN OF MBL-CUK CONVERTER

The energy transfer capacitors C1 and C2 are significant elements in the proposed MBL-CUK converter as their values largely impact the quality of input line current. Capacitors C1 and C2 must be selected so that their steady-state voltages get the shape of the rectified input ac line voltage waveform plus the output voltage with minimum switching voltage ripple as much as possible. Along with, the values of C1 and C2 should not induce low-frequency oscillations with the converter inductors. In a practical design perspective, the energy transfer capacitors C1 and C2 are decided on the basis of inductors L1, Lo values (assuming that L1=L2) in such a way that the resonant frequency (fr) during DCM stage is greater than the line frequency (fl) and well below the switching frequency (fs). Thus, On the contrary, the output capacitor Co requires being large enough to store minimum energy that is necessary for balancing the difference between the time varying input power and constant load power. The low-frequency peak-peak output voltage ripple is expressed by,

$$\Delta v_0 = \frac{1}{C_0}\int_{T_L/8}^{3T_L/8}[\bar{\imath}_{L_{o1}} - I_o]dt \quad (1)$$

where I_o refers the output load current, and $i_{L_{o1}}$ represents the average output inductor current over one switching cycle and it is expressed by

$$\bar{\imath}_{L_{o1}} = \frac{v_{ac}^2}{R_e V_o} \quad (2)$$

Replacing (2) into (1) and evaluating (1), the capacitor ripple equation is got as follows:

$$\Delta v_0 = \frac{V_0}{\omega R_L C_0} \quad (3)$$

$$f_1 < f_r < f_s \quad (4)$$

where,

$$f_r = \frac{1}{2\pi\sqrt{C_1(L_1+L_o)}} \tag{5}$$

4.1. Control (Voltage Follower Approach) of MBL-CUK CONVERTER

Figure 5 illustrates that the Control unit of MBL-CUK converter. The regulation of PFC converter helps in generation of the PWM pulses for the PFC converter switches (Sw1 and Sw2) for output voltage control with PFC operation at ac mains. A single voltage control loop (voltage follower approach) is employed for the PFC MBL-CUK converter that operates in DCM. The voltage error signal (V_e) is produced by comparing the reference output voltage(V_{OUT}^*) with the sensed output voltage (V_{OUT}) as

$$V_e(k) = V_{OUT}^*(k) - V_{OUT}(k) \tag{6}$$

where k denotes the kth sampling instant. This error voltage signal (V_e) is given as input to the voltage proportional–integral (PI) controller for generating a controlled output voltage (Vcc) as

$$V_{cc}(k) = V_{cc}(k-1) + k_p\{V_e(k) - V_e(K-1)\} + k_i V_e(k) \tag{7}$$

where k_p and k_i are the proportional and integral gains of the voltage PI controller. At last, the output of the voltage controller is compared with a high frequency sawtooth signal (md) in order to generate the PWM pulses as $sw_1$and sw_2, where Sw_1 and Sw_2 denote the respective switching signals to the switches of the PFC converter.

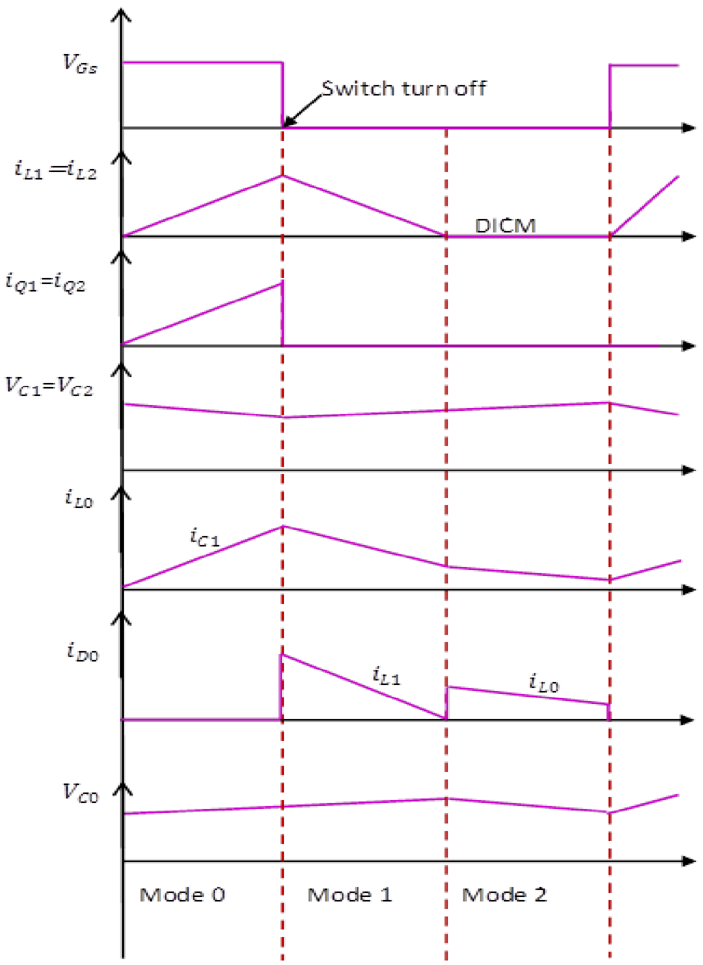


Figure 4. MBL-CUK converter performance

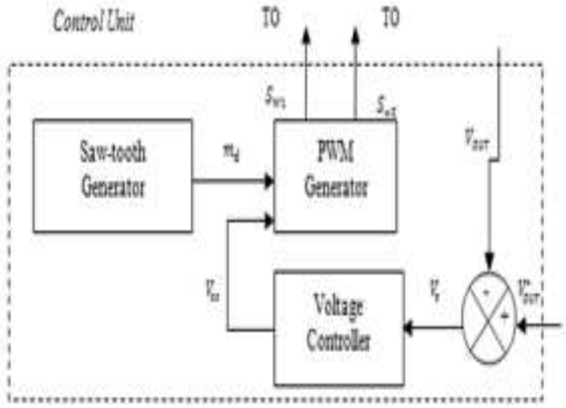


Figure 5. Control unit (Voltage Follower Approach) of MBL-CUK CONVERTER

5. RESULTS AND DISCUSSION

The performance of the proposed LED lamp driver based MBL-CUK converter is modelled in a MATLAB / Simulink environment making use of the SimPower-System Toolbox. The proposed MBL-CUK converter performance is assessed for both rated and dynamic situations and the attained power quality indices obtained at ac mains.

Parameters like supply voltage (V_{ac}), supply current (i_{ac}), input inductors L_1 and L_2 current (i_{L1}) and (i_{L2}), power switches Q1 and Q2 current (i_{Q1}) and (i_{Q2}), the intermediate capacitors$C_1$and C_2 voltage (V_{C1}) and (V_{C2}) respectively, (i_{D0}), (i_{Dp}) and (i_{Dn})denotes the current flowing through the Diode D_0, D_p and D_n, the corresponding converter output voltage, current and power(V_{OUT}), (I_{OUT}) and (P_{OUT}), of the proposed converter are investigated for demonstrating its proper functioning. In addition, power quality indices like power factor (PF), Displacement power factor (DPF), Total Harmonic Distortion (THD) of supply current are evaluated for deciding power quality at ac mains. The converter specifications that are utilized for the simulations are provided in Table 2.

Table 2. Specification

V_{ac_peak}	141.4 V
V_{ac_RMS}	100 V
I_{ac_peak}	2.28 A
I_{ac_RMS}	1.617 A
Input Power	161.7 Watts
Output Voltage	48 V
Output Current	3.125 A
Output Power	150 Watts
Efficiency	93%
Power Factor (PF)	0.9999

5.1. Steady-State Performance

Figure 6(a)-(e) illustrates the proposed converter operating at rated supply voltage of (141.4 V) and rated power on LED Lamp (150W) and rated voltage on LED Lamp (48V) respectively. As observed in these figures, the LED Lamp voltage, current and power is maintained at the necessary reference value as indicated in Figure 6(c-e). Here parameters like V_{OUT}^{*}, I_{OUT}^{*} and P_{OUT}^{*} indicate the desired reference voltage, current and power of LED Lamp respectively.

5.2. Proposed MBL-CUK Converter performance as Power Factor Preregulator

A sinusoidal supply current in phase with supply voltage is obtained as demonstrated in Figure 7(a), which indicates a near unity power factor at the instant the proposed converter works at rated power condition. Figure 7 (c) illustrates the discontinuous inductor currents $(iL1\ and\ iL2)$ with supply voltage in order to verify the DICM operation of the MBL-CUK converter. As observed in these figures, inductors Li1 and Li2 conduct for the respective positive and negative half-cycles of the supply voltage. Moreover, a continuous voltage across the intermediate capacitor (VC1 and VC2) is got, as seen in Figure 7(e).the current in diodes D1, D2 and power switches Q1, Q2 with respective to supply voltage is observed in Figure 7(b) and 7(d). As in these figures, during positive half cycle of supply voltage the diode Dp and switch Q1will conduct, similarly negative half cycle of supply voltage the diode Dn and switch Q2 will be conducting that shows the DCM operation of proposed MBL-CUK converter.

5.3. Dynamic Performance of the Proposed MBL-CSC Converter

The dynamic performance of the proposed converter during different values of output voltage is illustrated in Figure 8. It depicts the dynamic performance of the proposed converter fed LED Lamp during brightness control related to the step change in output voltage from 20 to 48 V at a peak supply voltage of 141.4V and the respective supply current variation is shown in Figure 8(a), 8(d) and 8(e). As observed in these Figures 8(a)-8(c), the converter output voltage, current and power is maintained at the necessary reference value with limited overshoot and undershoots. A smooth brightness control of LED Lamp is obtained, In addition supply voltage and current waveform caters a near unity power factor at both the values of converter output voltages as depicted in Figure 9(e).

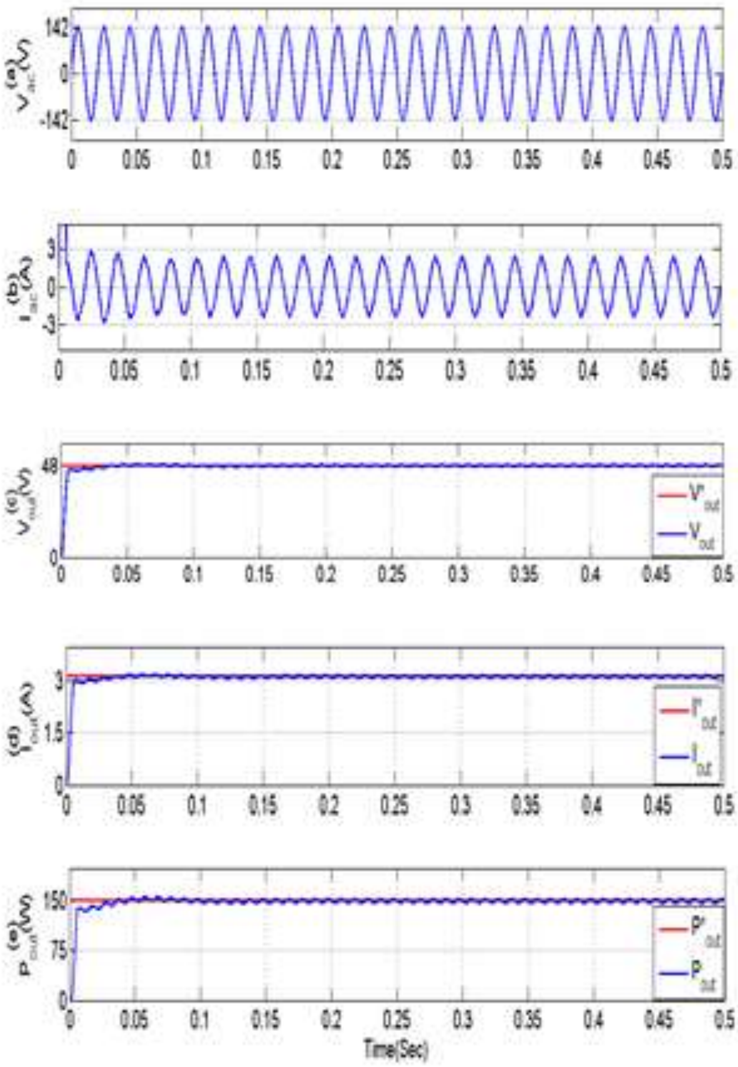


Figure 6(a)-(e). The proposed converter operating at rated supply voltage of (141.4 V)

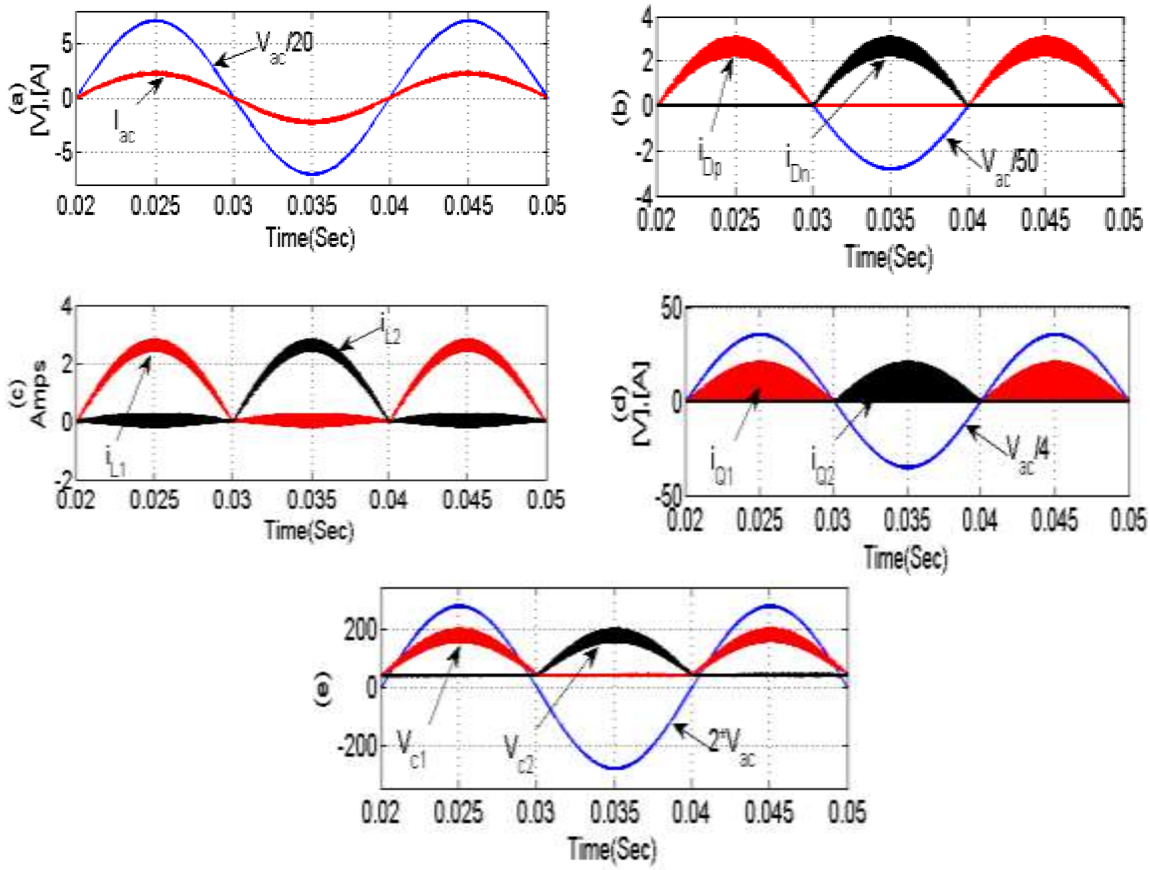


Figure 7(a -e). A sinusoidal supply current in phase with supply voltage

5.4. PFC and Improved Power Quality at AC Mains

This section involves the obtained power quality indices at the ac mains for the operation of the proposed converter at various values of output voltages. As depicted in the Table 2 the gained power quality indices received at ac mains are shown in the table when the output voltage is varied between 48 V to 20 V. A near unity power factor and displacement power factor is attained at the ac mains in all cases, In addition, the respective root mean square value of supply current, output power and Total Harmonic Distortion (THD) are also tabulated in Table 3.

Table 3. The root mean square value of supply current, output power and Total Harmonic Distortion (THD)

V_{out} (V)	*DPF*	PF	P_{out} (W)	I_{ac} (A) (Rms)	*THD%*
48	0.9999	0.9993	150	1.617	3.38
44	0.9999	0.9991	126	1.387	3.57
40	0.9996	0.9989	104	1.183	3.82
36	0.9994	0.9985	85	0.988	4.02
32	0.9992	0.9981	66.5	0.793	4.26
28	0.9991	0.9979	51	0.647	4.52
24	0.9989	0.9975	37.5	0.443	4.96
20	0.9988	0.9972	26	0.373	5.28

The harmonic spectra of the supply current at rated and light load conditions, i.e., LED Lamp voltages of 48V and 20 V, are also indicated in Figures 9(a) and (b), respectively, which, in turn, is helpful for exhibiting that the THD of supply current obtained is under the limits that are acceptable by IEC 61000-3-2.

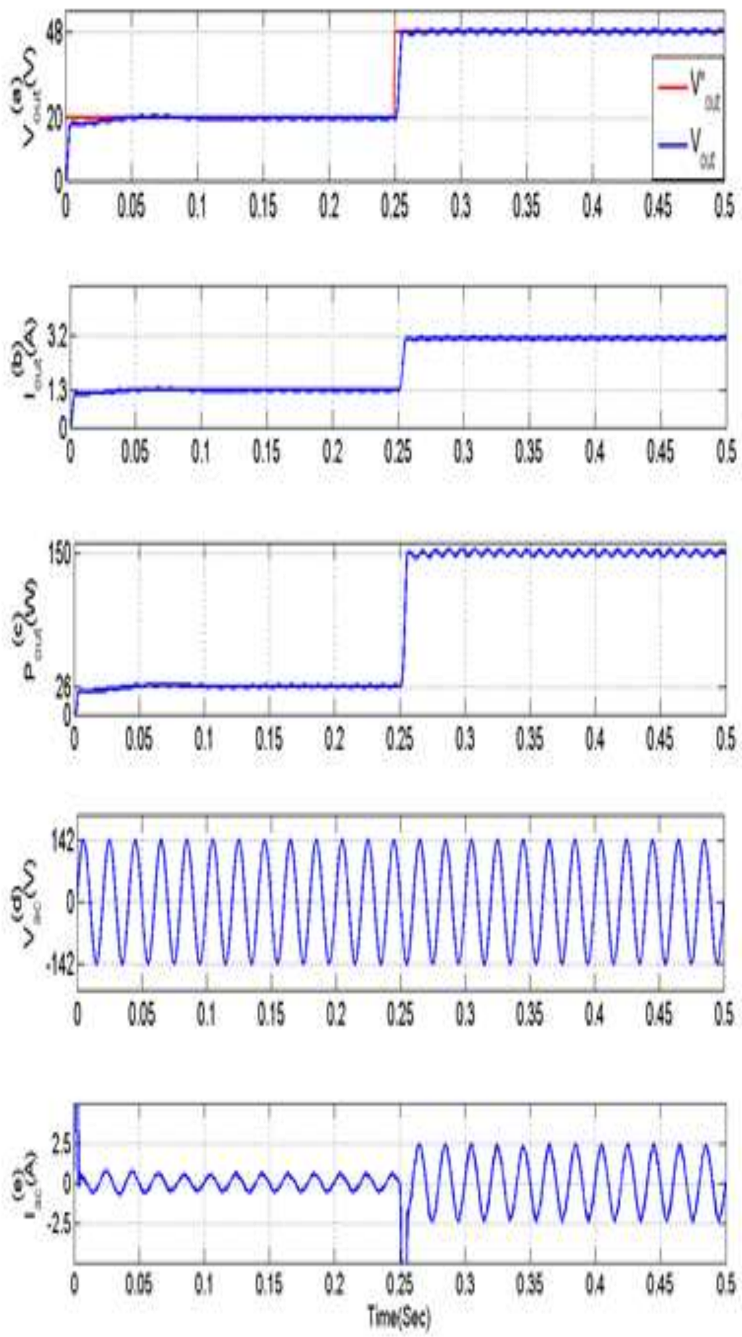
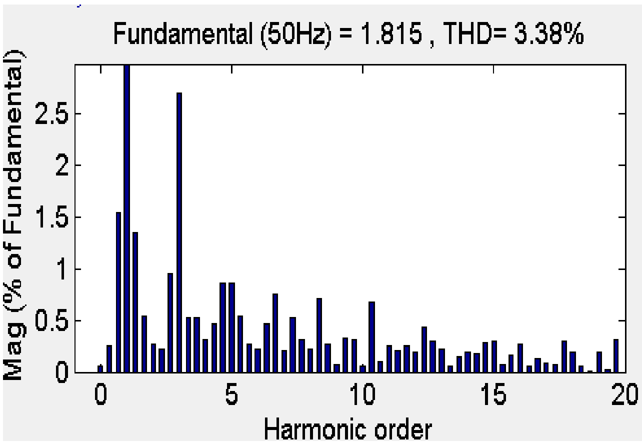


Figure 8. The dynamic performance of the proposed converter during different values of output voltage

5.5. Comparison of Efficiency of the Proposed Drive with the Conventional Scheme

The losses in a proposed converter comprises of the losses in the PFC converter. The losses in the PFC converter are estimated by having measurements of the output and input powers utilizing the corresponding output voltage, output current, supply voltage, and supply current. There are low losses in a PFC converter because of partial elimination of DBR and complete elimination of DC filter at the front-end converter, furthermore, the proposed converter minimizes the overall current conduction component during positive and negative half cycle of supply voltage, thereby helping in the reduction of the associated Conduction losses. Hence, a considerable increase in efficiency in the order of 2%–3% is accomplished in the proposed configuration.



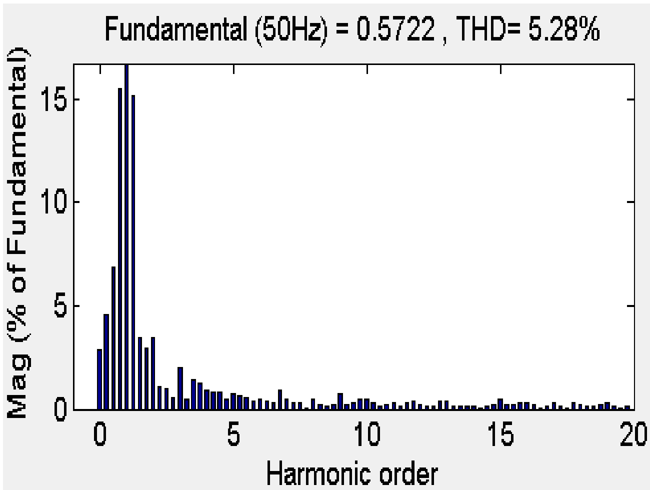


Figure 9. Harmonic spectra of supply current at rated input supply on LED Lamp and output voltage as (a) 48 V and (b) 20 V.

6. CONCLUSION

This paper proposed a novel MBL-CUK converter design for LED lamp applications. The proposed Bridgeless Cuk converter overcomes the limitations of the conventional PFC converter. The proposed PFC MBL-CUK converter focused on minimizing the overall power conduction devices when compared with the conventional PFC converter. The simulation results clearly show that the proposed work resulted in minimal THD and near unity power factor. Thus, the proposed converter resulted in considerable minimization of conduction losses with 2%-3% increased efficiency and reduced cost.

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