

High Efficiency Bridgeless Cuk Rectifier for High Voltage Battery Charging Applications

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Abstract

A step-up bridgeless single phase ac-dc power factor correction (PFC) rectifier based on Cuk topology is proposed for high voltage battery charger application. The proposed topology consists of common input stage and parallel output stages. It utilizes one control signal over the whole line cycle. In addition, the proposed converter exhibits low inrush current and low magnetic emissions as classical Cuk topology. The bridgeless topology results in lower conduction losses as compared with conventional Cuk converter. Simulation results are presented along with the theoretical analysis.

Keywords: *Bridgeless rectifier, Cuk topology, DCM, low in-rush current and PFC.*

1. Introduction

Power supplies with active power factor correction (PFC) techniques are required for wide range of applications for communication, automotive, computer and biomedical industries. All of these applications are required to meet industry standards such as the IEC 61000-3-2. In addition, it is highly recommended to meet new Industry standards such as the 80 PLUS initiative. Many papers have been published in the literature to provide a solution for single-stage power factor correction (PFC) integrated topologies [1-7]. These solutions have been effective to provide cost-effective approach for achieving both the function of high PFC and fast output voltage regulation.

Most of the PFC rectifiers utilize boost converter at their front end. Boost converter provides many advantages such as natural power factor correction capability and simple control. However, low voltage applications such as telecommunication or computer industry an additional converter or an isolation transformer is required to step down the voltage. However, classical boost arrangement has lower efficiency due to significant losses in the diode bridge [1]. In addition, boost converters suffer from high inrush current which increases the cost of safety required disconnection devices between the load and the line voltage. To minimize the losses of the full bridge, many bridgeless PFC rectifiers have been introduced to

improve the rectifier power density and/or reduced noise emissions [2]-[5] via soft switching techniques or coupled magnetic topologies. Several non-boost bridgeless rectifiers have been published lately [6]-[10]. A bridgeless PFC rectifier based on Sepic topology is presented in [8]. However, the topology has only a step up capability like a boost transformer; however, an isolation transformer can be used to step down the voltage, hence increasing the cost and size of the rectifier. Even though Cuk converter topology is typically a lower efficiency converter however it presents many advantages, such as isolation capability, step up/step down output voltage, continuous output current and lower electromagnetic emissions.

In this paper, high efficiency Cuk topology is proposed. The proposed topology is performance is evaluated based on component count, efficiency, total harmonic distortion (THD) and complexity. The proposed topology has an inherent low inrush current. In addition the proposed topology performance is compared with full bridge Cuk converter.

2. Proposed Cuk PFC converter

Figure 1a shows the proposed Cuk topology. This converter consists of single input stage for both the positive and negative half cycles of the line voltage. On the other hand, it has two output stages connected to the switched input voltage; each stage operates during one half line cycle. The converter active components during the positive half cycle are shown in Fig. 1b while the converter equivalent circuit during the negative half cycle is shown in Fig. 1c. The proposed converter utilizes two switches (Q1 & Q2). Q1 is turned on/off during the positive half-line cycle while Q2 is switched on/off during the negative half cycle. The converter has inherent high power factor when operating in discontinuous inductor conduction mode (DICM) because the line current is proportional to the input voltage.

The converter operation during the positive half-line cycle is discussed below

Stage 1 $[0, D_1T_s]$: In this stage, switch Q_1 is switched on and diode D_{o1} is reversed biased by the capacitor voltage (V_{c1}). The output diode D_{o2} is reversed biased by capacitor voltage (V_{c2}). The input voltage is connected to ground directly. The three inductors are charging up by the input voltage as shown in Fig. 2a. This stage ends when switch Q_1 is turned off.

Stage 2 $[D_1T_s, D_2T_s]$: This stage starts after Q_1 is switched off and diode D_{o1} turns on simultaneously as shown in Fig. 2b to provide current path for the output inductor current L_{o1} . This stage ends when diode (D_{o1}) current goes to zero.

Stage 3 $[D_2T_s, T_s]$, this stage is reached when both the active switch and the output diode are off. The equivalent converter circuit of this stage is shown in Fig. 2c. Notice that there are no semiconductor devices conducting in this stage. The freewheeling stage ends when the new switching period starts. It shall be noted that to guarantee DCIM operation D_2T_s must be less than T_s . Theoretical inductor currents waveforms over one switching cycle during the positive half cycle of the input voltage are shown in Fig. 3.

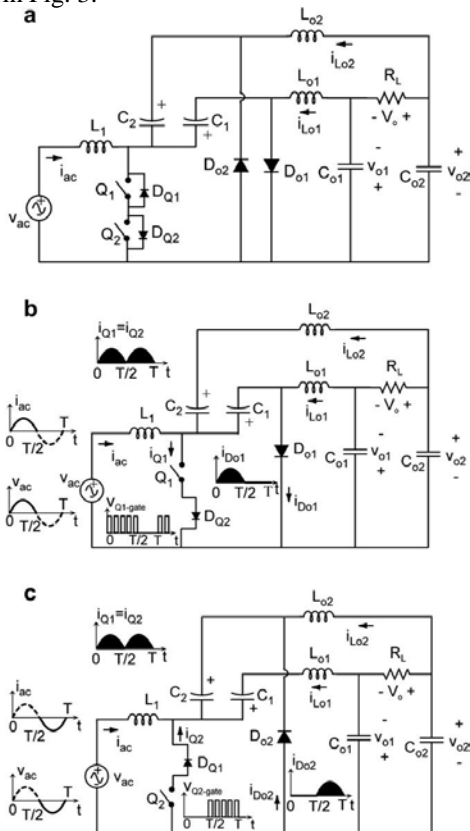


Fig.1 (a) Proposed bridgeless Cuk rectifier (b) Positive half line cycle, (c) Negative half line cycle.

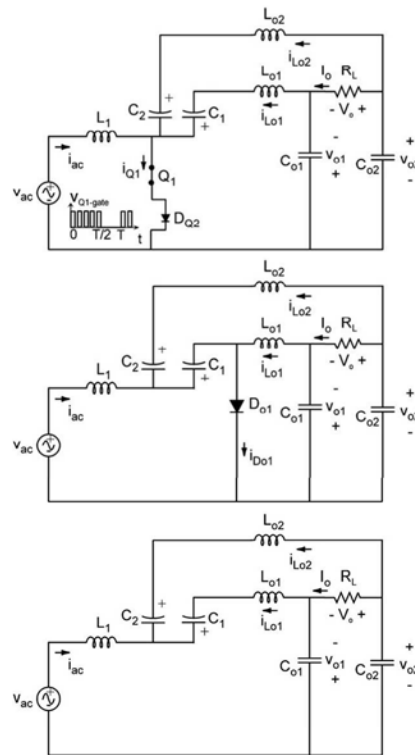


Fig 2. The converter equivalent cycle over one switching cycle (a) First stage, (b) Second stage, and (c) Third stage.

Due to the symmetry of the circuit, it is sufficient to analyse the circuit during the positive half cycle of the input voltage. By operating the rectifier in DCM, several advantages can be gained. These advantages include natural near-unity power factor, the power switches are turned ON at zero current, and the output diodes (D_{o1} and D_{o2}) are turned off at zero current. Conversely, DCM operation significantly increases the conduction losses due to the increased current stress through circuit components. As a result, this leads to one disadvantage of the DCM operation, which limits its use to low-power applications.

Fig. 3 shows the main theoretical waveforms during one switching period. The energy transfer capacitors C1 and C2 are important elements in the proposed Cuk topologies since their values greatly influence the quality of input line current. Capacitors C1 and C2 must be chosen such that their steady-state voltages follow the shape of the rectified input ac input voltage. Also, the values of C1 and C2 should not cause low-frequency oscillations with the converter inductors. In a practical design, the energy transfer capacitors C1 and C2 are determined based on inductors L_1, L_o values (assuming $L_1 = L_2$ and $L_{o1} = L_{o2} = L_o$) such that the resonant frequency (f_r) during DCM stage is higher than the line frequency (f_l) and well below the switching frequency (f_s). On the other hand, the output

capacitors needs to be sufficiently large to store minimum energy required for balancing the difference between the time varying input power and constant load power.

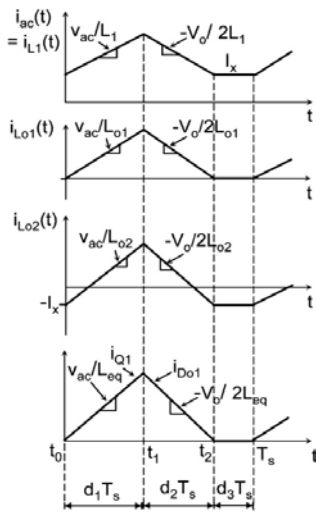


Fig. 3. Theoretical waveforms for the proposed converter.

3. Simulation Results

The proposed modified Cuk rectifier is designed for the following operating point: peak input voltage of 100 V_{rms}, line frequency of 50 Hz, output voltage of 250 V, switching frequency of 50 kHz, and output power of 125 W. The circuit components used in the simulation are chosen as follows: L₁ = 2 mH, L_{o1} = L_{o2} = 50 μH.

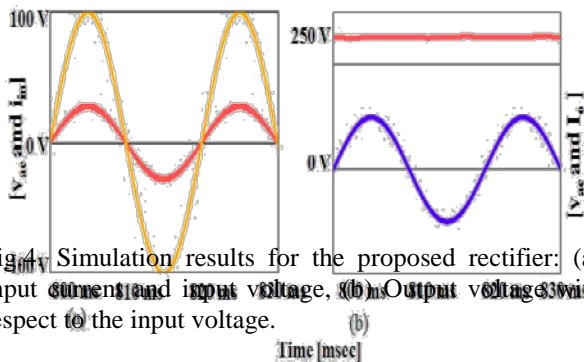


Fig.4. Simulation results for the proposed rectifier: (a) Input current and input voltage, (b) Output voltage with respect to the input voltage.

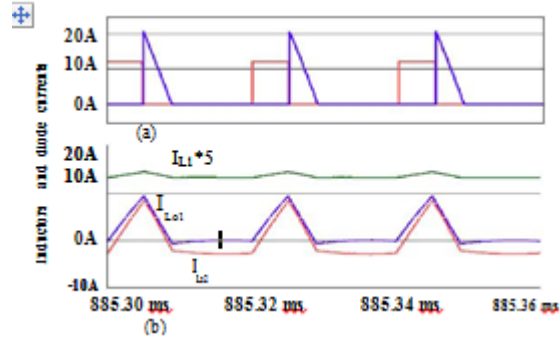


Fig.5. Simulation results: (a) V_{Q1} and i_{Do1}, (b) I_{L1}, I_{Lo1}, and I_{Lo2}.

The input voltage and current are in-phase as shown in Fig. 4(a). The total harmonic distortion in the line current is 0.17% and the efficiency is 94%. The output voltage with respect to the input voltage is shown in Fig. 4(b), where the output voltage meets the requirements. It should be noted that the diode starts conducting after the switch is turned off and the current goes to zero before the end of the cycle which ensures DCM as shown in Fig. 5(a). Fig. 5(b) shows the three inductor currents over a switching cycle. The inductor currents have proportional slopes over the three different stages of a switching cycle. Thus, the three inductors can be coupled which lead to lower costs and smaller size. In addition, the three inductors are being charged by the input voltage when the Q₁ is conducting, but when the diode D_{o1} is conducting, the three inductors are discharging through the output capacitors.

4. Conclusions

A bridgeless Cuk rectifier operating in DICM has been introduced. The Cuk rectifier has lower number of silicon components in the current path versus the conventional full bridge Cuk rectifier; hence higher efficiency is possible. The capability of this topology is verified using simulation results. Converter efficiency of 94% is achieved at low input voltage of 100 V_{rms}. The proposed circuit meets IEC-1000-3-2 requirements. The proposed rectifier at 125W and full load has THD of 0.17%.

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