Engineering Science and Technology, an International Journal xxx (2018) xxx–xxx

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Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Design and experimental evaluation of a single-stage AC/DC converter with PFC and hybrid full-bridge rectifier

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A R T I C L E I N F O

Article history:
Received 30 November 2017
Revised 2 February 2018
Accepted 3 March 2018
Available online xxxx

Keywords:
LED streetlight
AC/DC converter
Power factor correction
LLC resonant
Full-bridge rectifier

A B S T R A C T

This paper presents design and experimental evaluation of a single-stage AC/DC converter with PFC and hybrid full-bridge rectifier for supplying LED streetlight. The proposed converter consisted of one LLC resonant tank, two boost circuits and one shared inductor. By incorporating a relay switch at the secondary-side of the circuit, the output stage can be operated as two different types of rectifier: the first is as a full-bridge rectifier and the second type is as a full-bridge voltage doubler rectifier. The proposed converter was designed to receive a 240-V, 50-Hz single-phase AC supply as its input. MATLAB Simulink software was used to simulate the proposed converter, and later, a prototype was built for the experimental measurements at 100-W rated output power. The experimental results and the performance of the proposed converter were analyzed for PFC, efficiency, THD, and bus voltage. The proposed converter can achieve soft-switching characteristics since the power switches and output diodes were operated with ZVS and ZCS conditions, respectively. Furthermore, when the relay switch was closed, the output voltage was twice higher than that of when the relay switch was opened. The maximum efficiency of the proposed converter with hybrid full-bridge rectifier and full-bridge voltage doubler rectifier was about 92.6% and 93.3% respectively.

1. Introduction

Light-emitting diode (LED) lights have become the most well-known type of lights, owing to their good features such as energy saving, long life-span, good luminous efficacy and low maintenance costs. LED lights are suitable for usage in various locations and fields, such as at home, commercial or office buildings, factory, outdoor premises and automotive. However, the evaluation of the performance of LED lights depends on the values taken from measurement of the power factor correction (PFC), efficiency and total harmonic distortion (THD) of the LED driver [1–4].

Switch-mode power converters have gained popularity in the industrial, commercial and residential sectors due to their advantages such as high efficiency, smaller weight and size [5–8]. The PF could reach up to unity in active power factor correction (PFC) by using switched-mode power supply (SMPS) method. There are a few operating modes for PFC applications such as continuous conduction mode (CCM), boundary conduction mode (BCM) and discontinuous conduction mode (DCM), but CCM and BCM have been widely used in the boost converters [9–12].

Lately, however, the engineers have started to deploy a higher switching frequency on SMPS, which led to greater increase in switching losses in pulse width modulated converters, hence, decreasing the efficiency [13,14]. Most of the buck converters based on LED lighting are typically appropriate for general AC inputs. These converters use efficient transformerless drivers and feature the benefit of lower output voltage because of the smaller output capacitance. Nevertheless, without proper isolation, these converters need extra concern related to the protection requirement [15–17]. While, the boost converters based on LED lighting are usually preferable for high power LEDs connected in series and simply to be designed to realize high system efficiency. In comparison with buck converters, both the switch and LED lighting loads of the boost converters are connected to the common ground which significantly help in LED current sensing. However, the output current has usually larger ripple in these boost converters. Therefore, a large capacitor is required which may effect the LED dimming capability [18,19].

The buck-boost converters are very appealing option for low and medium power LED lighting applications which has less costly design. Certainly, with one inductor, the converters are similarly

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Peer review under responsibility of Karabuk University.

https://doi.org/10.1016/j.jestch.2018.03.003
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considered equal to the transformer based on flyback converters. Despite the fact that the converters are able to operate as step-down or step-up circuit, the converters also produce negative output voltage [20,21]. The flyback converters can acquire high PF, and at the same time, have output current regulation. Due to high switching losses, the efficiency of these converters is less than 87%. Consequently, to realize these converters in high power applications, the leakage inductance and parasitic capacitance of the flyback transformer needs to be reduced for better performance [22,23]. The buck, boost and buck-boost converters operating in DCM are commonly adopted as PFC circuit on the primary-side, while in the flyback converter, they are applied in the secondary-side in order to regulate the output voltage.

Therefore, resonant converter topologies have been considered as one of the possible solutions. Resonant topologies, also known as resonant tank circuits have three basic types: series, parallel and series-parallel. They consist of reactive elements such as capacitors and inductors. The series and parallel resonant topologies consist of a single capacitor and an inductor element, but the series-parallel resonant topology consists of either: (a) two capacitors and an inductor (LCC resonant topology); or (b) two inductors and a capacitor (LLC resonant topology). Nevertheless, the LLC resonant type is the most popular converter [24–27]. When the resonant tank is used, the semiconductor switches can operate at zero-current switching (ZCS) or zero-voltage switching (ZVS) conditions, which leads to a reduction of switching losses and allows the converters to operate at high switching frequencies [28–31].

Researchers in [32] proposed a ZVZCS single-stage PFC AC-to-DC half-bridge converter with two bus capacitors. This converter was virtually a low-cost design which can produce a nicely regulated output with high power factor, but this converter is not appropriate for high input voltage application due to its high bus voltage which is double than the input voltage. Therefore, it leads to higher power rating on the capacitor and more stresses on the power swicthes. In [33], the researchers conducted an analysis and a design of a single-stage LLC resonant with PFC boost converter, to ensure that the bus capacitor voltage has a suitable value. They also derived the relationship between the output power of the boost PFC converter and the LLC converter, but it was not appropriate for high input voltage.

Another researcher in [34] suggested an LLC series resonant converter based LED driver with PFC boost converter which was operated in CCM, and a quasi-half bridge resonant converter that worked under ZVS to reduce switching losses. The proposed converter achieved a constant voltage and current, which were required to drive high brightness LED lamps, but it has high DC bus voltage level and high cost compared to a single-stage AC/DC converter. A single-stage LED driver based on double LLC resonant tanks for automobile headlight with digital control has been proposed in [35]. This converter has less current stress on the power switches and applicable for high input voltage application because it kept the bus voltage constant to be less than 350-V. Nevertheless, the converter consisted of two resonant tank circuits which potentially increased the size of the converter.

In this paper, a single-stage AC/DC converter which has two boost circuits and one shared inductor with LLC resonant tank was proposed. The two boost circuits operated in BCM, achieved good PFC function. This topology was suitable to work under high input voltage conditions because the bus voltage was almost at the same level as the peak input voltage. This study aims to improve the performance of the proposed converter by making the converter capable to operate at the output stage as hybrid full-bridge rectifier with better efficiency. By connecting a relay switch at the output stage, the output voltage can be obtained either from the full-bridge rectifier or from a full-bridge voltage doubler rectifier.

2. Description and circuit diagram

The circuit diagram of the proposed single-stage AC/DC converter with PFC and hybrid full-bridge rectifier is shown in Fig. 1. It consisted of the following components: an AC voltage source, V_{in}; a full-bridge rectifier, D_{i1}, D_{i2}, D_{i3} and D_{i4}; two voltage divider capacitors, C_1 and C_2; a boost inductor, L_b; two power switches, SW_1 and SW_2 with two snubber capacitances, C_{s1} and C_{s2}; and two parasitic diodes, D_{p1} and D_{p2}; two boost diodes, D_{b1} and D_{b2}; a bus voltage capacitor, C_{bus}; a LLC resonant tank that consisted of series resonant capacitor, C_r; series resonant inductor, L_r; and magnetizing inductor, L_m; a power transformer, four output diodes, D_{r1}, D_{r2}, D_{r3} and D_{r4}; two output capacitors, C_{o1} and C_{o2}; a relay switch, SW_r; and an output load resistor, R_{led}.

Each of the voltage divider capacitors, C_1 and C_2 has a half DC input voltage. The capacitors, C_1 and C_2 were considered as the source of DC input voltage for the proposed converter, which also worked as a filter capacitor for the DC input voltage. There were two PFC boost circuits and both shared the bus capacitor, C_{bus} and boost inductor, L_b which led to reducing the number of passive components in the proposed converter. The power switches, SW_1 and SW_2 were connected in the form of a half-bridge structure of the LLC resonant converter.

The output diodes were connected in the form of a full-bridge rectifier, the output capacitors were connected together in series and in parallel with the output wave rectifier. One terminal of the relay switch, SW_r was connected between the two output capacitors, C_{o1} and $C_{o2,}$ and the other terminal was connected between the diodes, D_{r2} and D_{r3} of the bridge rectifier. There were two states of relay switch, SW_r operation, either opened (0) or closed (1) as seen in Fig. 2.

3. Operations principle and steady-state analysis

The operation of the proposed converter can be divided into eight modes in one switching cycle. When the SW_r is opened, the key steady-state waveforms and equivalent circuits for these eight modes of operation as shown in Figs. 3 and 4, respectively. The details of the operations of the first half cycle are explained below and thereafter, the effect of changing the relay switch, SW_r state from open to close will be clarified.

Mode 1 (t_0–t_1): At the beginning of this mode, the snubber capacitor, C_{s1} of power switch, SW_1 has been discharged completely by the resonant current, I_{Lr} flowing in reverse direction. In other words, the current flows through the parasitic diode, D_{p1} of the power switch, SW_1 that starts to conduct. Since, the drain-

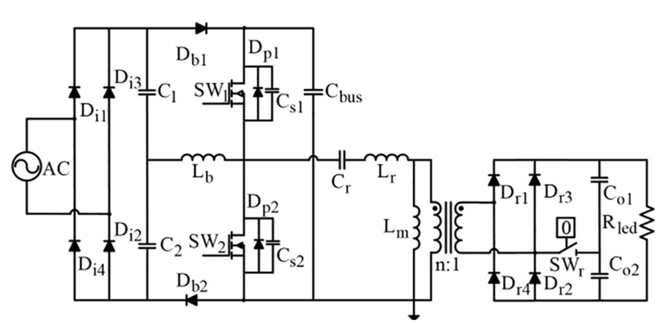

Fig. 1. Circuit diagram of proposed single-stage AC/DC converter with PFC and hybrid-full-bridge rectifier.

Please cite this article in press as: N.A. Samsudin et al., Design and experimental evaluation of a single-stage AC/DC converter with PFC and hybrid full-bridge rectifier, Eng. Sci. Tech., Int. J. (2018), https://doi.org/10.1016/j.jestch.2018.03.003