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Input Controlled Series-Resonant Converter for LED Lighting Application

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***Abstract*—This paper proposes an input voltage regulated series resonant converter for LED lighting applications. Two inputs used in the proposed converter are obtained either from PV system or battery. A buck-boost DC-DC converter is cascaded with the series resonant converter such that it regulates the input of series resonant converter for PV/battery voltage variations. Thus the series resonant converter is always operated with constant frequency and duty cycle and hence achieves the advantages like low EMI, ZVS in wide range, etc. The buck-boost converter is operating under low power, hence power losses are minimized. PWM dimming is also implemented in this converter for controlling LED illumination level. The circuit description, analysis and simulation results are discussed further.**

***Index Terms*—Series-resonant converter, ZVS, buck-boost converter, LED**

I. Introduction

A large amount of energy conservation is possible with effective utilization of electrical energy for lighting application. In this regard, Light Emitting Diode (LED) lighting is becoming popular now-a-days. In addition to high efficacy, it also has advantages like long life, instant turn ON/OFF, compact size, etc. LED lighting requires DC input which can be derived from either DC or AC supply. For low power applications LED is driven by DC source. Renewable energy sources like Photovoltaic (PV) system or a simple battery can be used. An LED driver is the one which regulates the output of LED load for input variations with high efficiency, dimming feature etc.

Various kinds of LED driver configurations are presented in the literature. LEDs are driven by either linear regulators or switched mode power supplies (SMPS). SMPS are mostly preferred as they have high efficiency [1], [2]. In [3], dual input LED driver using buck converter is presented to reduce voltage stress in switching device. Interleaved buck converter based LED driver is proposed in [4], where there is reduction of current ripple. Soft switched LED drivers are developed to reduce switching losses and hence increase efficiency. Zero current switching (ZCS) based LED driver is proposed in [5] to increase efficiency. Resonant converter based LED drivers are becoming more popular as they possess advantages like low EMI noise, low power density, soft switching across devices. Class-D resonant topology based LED driver with soft switching is implemented in [6]. Half-bridge and full-bridge topologies are widely used for implementing series, parallel and series-parallel resonant based LED drivers. Full-bridge topologies are preferred due to their high power handling capability. Full bridge resonant converter for multiple string LED applications is proposed in [7]. In [8], resonant converter based buck converter is proposed as LED driver.

Full bridge series resonant converter using is easier to implement and therefore mostly preferred. In [9], resonant full bridge converter topology is cascaded with DC bus for LED lighting applications. The LED cut-in voltage is supplied from DC bus and the resonant converter regulates LED current. However, it is difficult to achieve Zero Voltage Switching (ZVS) at all input variations and also design of the converter is complex. In this paper, a new LED driver based on series resonant converter cascaded in series with buck-boost converter is proposed for LED lighting applications. PV source or battery can be used as the input to the proposed converter. The LED driver output is regulated using buck-boost converter for input voltage variations. Hence, the LC series resonant converter is operated with constant duty cycle at constant frequency. This makes the design of series resonant converter simple and also ZVS is perfectly achieved irrespective of input voltage variations. The losses in the buck-boost converter are also less as the power handled by it is low. Dimming is a technique adopted to control the illumination level of LED lighting. Amplitude modulation and pulse width modulation (PWM) dimming techniques are the most popular dimming techniques available. PWM dimming is implemented in the proposed converter as it controls the average LED current without altering its peak value and thus the LED characteristics remain unaffected. Proposed LED driver configuration is described in section-II. Principle of operation with its analysis is presented in section-III. Regulation of LED current and dimming methodology are discussed in section-IV. Design procedure is discussed in section-V. In section-VI, simulation results are discussed with conclusion in section-VII.

II. Proposed LED Driver Configuration

Fig. 1 shows the circuit diagram of proposed LED driver which consists of a series resonant converter cascaded in series with buck-boost converter with two DC inputs V_{DC1} & V_{DC2}. Series resonant converter consists of a full bridge inverter

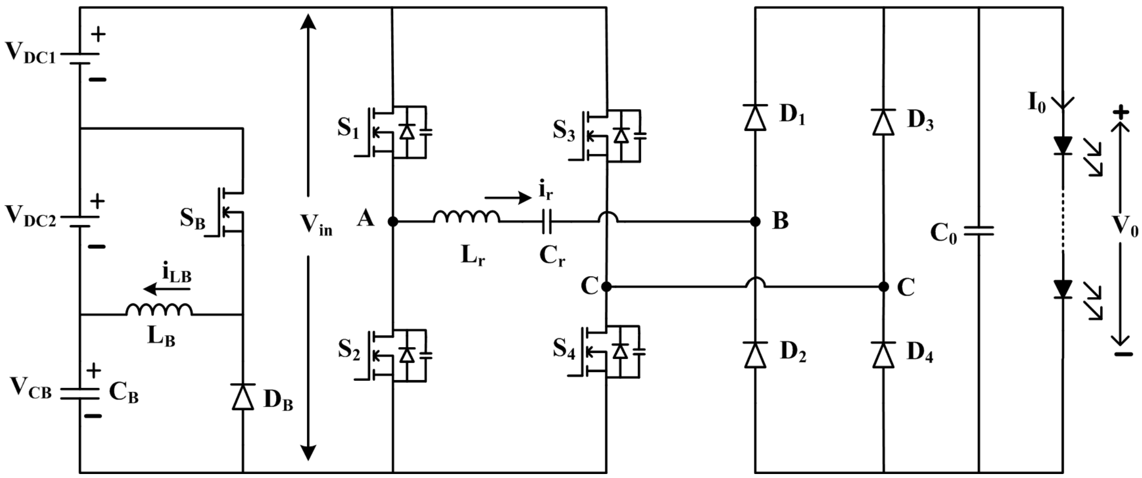


Fig. 1. Proposed LED driver

connected to full-wave diode rectifier with series resonance elements L_r & C_r. Full-bridge inverter consists of four MOSFET switches- S_1, S_2, S_3 and S_4 with body diodes and snubber capacitors. Snubber capacitors across switches also include internal parasitic capacitance of switches. The diode bridge rectifier consists of diodes- D_1, D_2, D_3 and D_4. LED lighting load is connected at the output of diode bridge rectifier with filter capacitor, C_o. The elements of buck-boost converter are output capacitor C_B, MOSFET switch S_B, inductor L_B and free wheeling diode D_B. This converter is driven from V_{DC2}. V_o & I_o are respectively the output voltage and current of LED string. V_{in} is the total voltage applied to series resonant converter. i_r is the resonant current flowing in resonant circuit elements and i_{LB} is the current flowing in inductor L_B .

III. Principle of Operation and Analysis

A. Principle of Operation

The input voltage applied to series resonant converter is the sum of the voltages, V_{DC1}, V_{DC2} & V_{CB}. The buck-boost converter is operated at constant switching frequency. Duty cycle of buck-boost converter is varied such that it maintains the input voltage applied to series resonant converter constant irrespective of any input voltage variations. Thus, the switches in each leg of inverter are operated alternatively with 50 % duty cycle at fixed frequency. The corresponding operating waveforms of the proposed converter are shown in Fig. 2, where V_{g1}, V_{g2}, V_{g3} & V_{g4} are the gate voltages applied to inverter switches. Bridge inverter produces a symmetric voltage and is applied across diode bridge rectifier through series resonant elements. The fundamental component of resonant current is sinusoidal in nature as shown in Fig. 2. The rectified square wave voltage from bridge rectifier is filtered and applied to LED string. Because of series resonance developed, ZVS is achieved in the inverter switching devices. Hence switching losses are minimized and high efficiency is achieved. As the resonant converter is operated with fixed frequency and duty cycle, ZVS operation is possible for wider range of

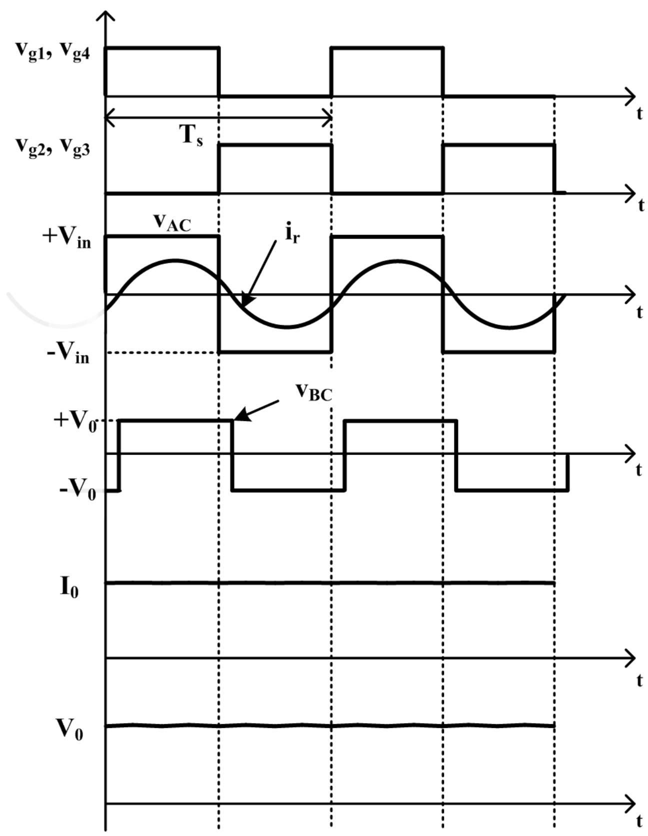


Fig. 2. Operating waveforms of proposed LED driver

input voltage and design of the resonance and snubber circuit becomes simple. The buck-boost converter is driven with reduced voltage of V_{DC2} hence that it is operated effectively with optimum duty cycle and better efficiency.

B. Analysis of Proposed Converter

The following assumptions are made to analyse the proposed LED driver configuration:

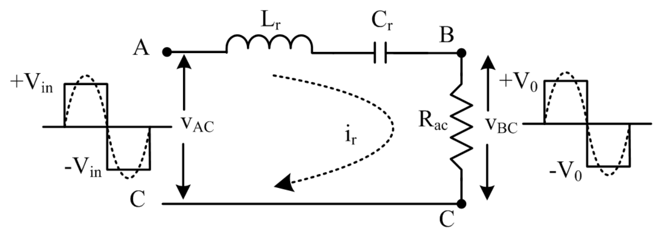


Fig. 3. AC equivalent circuit

- The proposed converter is operating in steady state.
- The power MOSFETs and power diodes used are ideal.
- The voltage across LED lamp is constant.

The duty ratio, D_B of the buck-boost converter is expressed as

$$D_B = \frac{|V_{CB}|}{V_{DC2} + |V_{CB}|} \tag{1}$$

The critical inductance of the buck-boost converter is expressed as

$$L_{Bmin} = \frac{(1 - D_B)^2 R_B}{2 f_B} \tag{2}$$

where f_B is the switching frequency and R_B is the output resistance of buck-boost converter. For continuous inductor current, $L_B > L_{Bmin}$. The input voltage applied across full bridge inverter can be expressed as

$$V_{in} = V_{DC1} + V_{DC2} + V_{CB} \tag{3}$$

When this V_{in} is applied across inverter, a square wave voltage of magnitude V_{in} is generated through switching action which is applied to $L_r - C_r$ network. Hence, conventional ac analysis can be used to calculate the static gain of the converter. The ac equivalent circuit of proposed driver circuit is shown in Fig. 3. The ac resistance R_{ac}, which is used in ac equivalent circuit, accounts for the non-linearity present in rectifier. The reactances offered by L_r and C_r are denoted as X_L and X_C respectively where

$$X_L = 2\pi f L_r \quad \& \quad X_C = \frac{1}{2\pi f C_r} \tag{4}$$

From Fig. 3, static gain of the proposed driver is represented by using simple voltage division principle:

$$\frac{V_{BC}}{V_{AC}} = \frac{R_{ac}}{R_{ac} + j(X_L - X_C)} \tag{5}$$

Since both v_{BC} and v_{AC} are square wave voltages, the static gain in terms of actual proposed LED driver values is given by

$$\frac{V_o}{V_{in}} = \frac{1}{\left[1 + j\left(\frac{X_L - X_C}{R_{ac}}\right)\right]} \tag{6}$$

R_{ac} can be obtained as [10],

$$R_{ac} = \frac{8}{\pi^2} R_{eff} \tag{7}$$

where R_{eff} is the resistance offered by LED string.

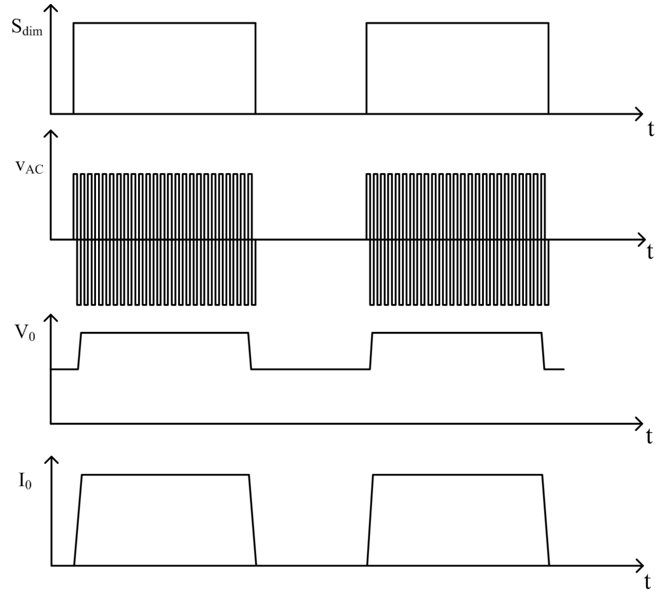


Fig. 4. Dimming waveforms in the proposed converter

The sharpness in the current is measured by quality factor (Q), and it is defined by

$$Q = \frac{\omega_r L_r}{R_{eff}} = \frac{1}{\omega_r C_r R_{eff}} \tag{8}$$

where ω_r is the angular frequency given as

$$\omega_r = 2\pi f_r = \frac{1}{\sqrt{L_r C_r}} \tag{9}$$

where f_r is resonant frequency. By substituting (4), (7) and (8) into (6), the gain is finally expressed as

$$\frac{V_o}{V_{in}} = \frac{1}{\left[1 + j\frac{\pi^2}{8} Q\left(\frac{f_s}{f_r} - \frac{f_r}{f_s}\right)\right]} \tag{10}$$

IV. Regulation of LED current and Dimming Control

In the proposed configuration, switches in inverter bridge are operated with fixed duty cycle. Therefore LED lamp brightness must be regulated against variations in dc voltages V_{DC1} & V_{DC2}. Buck-boost converter is used to regulate LED output. Duty cycle of buck-boost converter is adjusted for input voltage variations such that there is always a constant output at LED string.

In the proposed study, PWM dimming is implemented by ANDing the gate pulses of inverter with a low frequency dimming signal, S_{dim} such that the output of inverter is alternatively switched ON and OFF as shown in shown in Fig. 4. This makes the LED lamp ON and OFF at selected operating voltage and current. Hence, average current through lamp is controlled. The dimming signal, inverter output voltage, LED lamp current and voltage are shown in Fig. 4. It can be observed that the LED output voltage, V_o reduces to threshold voltage when V_{AC} is OFF and thereby the LED current, I_o reduces to zero respectively.

V. Design Considerations

To select the component values of proposed driver, the equivalent electrical parameters of LED load must be considered. The equivalent circuit of LED is represented by a series connection of a cut-in or threshold voltage V_{th}, a dynamic resistance r_d and an ideal diode. The LED load comprises of 4 parallel LED strings. Each string consists of 8 LEDs connected in series. Each LED is operated with a voltage of 3.25 V and 500 mA with a threshold voltage of 2.3 V. So total LED lighting load is operated with 26 V and 2 A with a threshold voltage of 18.4 V. Consequently power consumed by LED load is 52 W.

A. Selection of input dc voltages, V_{DC1} and V_{DC2}:

To achieve the required output voltage, V_o of 26 V, across LED string, input voltage, V_{in} is computed as 30.5 V from (10). To reduce the power loss in buck-boost converter, V_{DC1} & V_{DC2} are chosen as 12 V each. The remaining input voltage is compensated by buck-boost converter.

B. Calculation of L_B:

The switching frequency, f_B of buck-boost converter is chosen as 125 kHz. By using (1) and (2), the inductance L_{Bmin} is calculated and for the inductor current to be continuous, L_B chosen more than L_{Bmin} as 30 μH.

C. Calculation of L_r and C_r:

The product of L_r and C_r is obtained from (9) and it is expressed as

$$L_r C_r = \left[\frac{1}{2\pi f_r}\right]^2 \tag{11}$$

By choosing switching frequency, f_s of inverter as 125 kHz and the ratio f_s/f_r as 1.1, the above equation can be expressed as

$$L_r C_r = 1.974 \times 10^{-12} \tag{12}$$

From (12), the elements L_r and C_r are selected as 42 μH and 4.7 nF respectively.

TABLE I
Design Parameters

Parameters	Values
DC Input voltage, V_{in}	30.5 V
Switching frequency, f_s	125 kHz
Resonant frequency, f_r	113.6 kHz
Resonant inductor, L_r	42 μH
Resonant capacitor, C_r	0.047 μF
Output capacitor, C_o	2.2 μF
Output voltage, V_o	26 V
Output current, I_o	2 A
Output power, P_o	52 W
Frequency of buck-boost converter, f_B	125 kHz
Buck-boost inductor, L_B	30 μH
Buck-boost capacitor, C_B	100 μF
PWM dimming frequency	100 Hz
Switching devices used	IRF 540N
Power diodes used	MUR 860

VI. Simulation Results

To verify the feasibility of proposed configuration, a 52 W prototype is simulated using OrCAD PSpice software. Table I shows the parameters of the proposed LED driver. Fig. 5 shows simulation waveforms of the converter at rated load. Fig. 5(a) shows the buck-boost converter gate voltage, V_{gB} inductor current, i_{LB} and its output voltage, V_{CB}. Fig. 5(b) shows inverter input voltage and its current. Fig. 5(c) shows bridge rectifier input voltage and its current. Fig. 5(d) shows voltage and current through LED lamp at full illumination. They are in good agreement with the theoretical analysis. The efficiency of the driver at full illumination level is estimated using PSpice which is found to be 92.67%. The simulation efficiency obtained is near to the practical efficiency as the switching devices and diodes used are modelled from the data sheets of the devices.

To test the converter performance, ±5% variations in V_{DC1} & V_{DC2} are considered. Fig. 6 and Fig. 7 shows simulation waveforms of the converter with +5% and -5% input voltage variations. The efficiencies are found to be 92.20% and 91.93% respectively.

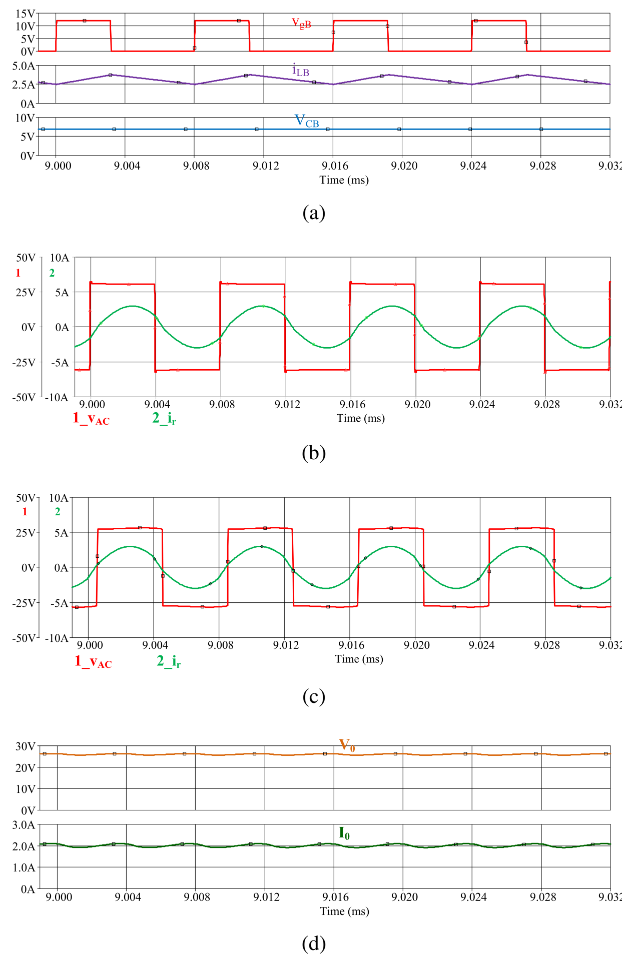
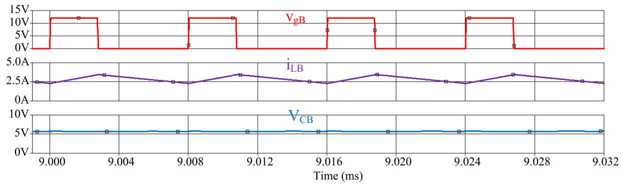
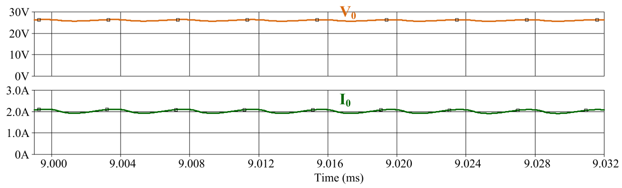


Fig. 5. Simulation waveforms at rated load: (a) Waveforms of V_{gB}, i_{LB} & V_{CB} (b) Waveforms of v_{AC} & i_r (c) Waveforms of v_{BC} & i_r (d) Waveforms of v_o & i_o

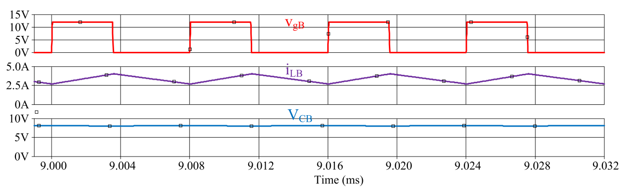


(a)

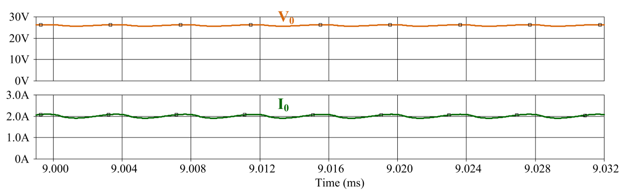


(b)

Fig. 6. Simulation waveforms at +5% input voltage: (a) Waveforms of V_{gB}, i_{LB} & V_{CB} (b) Waveforms of v_o & i_o



(a)



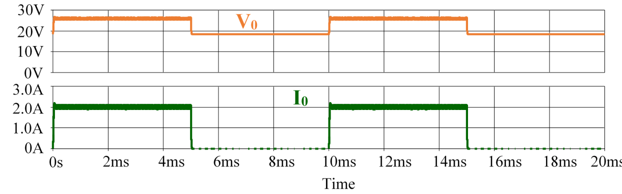
(b)

Fig. 7. Simulation waveforms at -5% input voltage: (a) Waveforms of V_{gB}, i_{LB} & V_{CB} (b) Waveforms of v_o & i_o

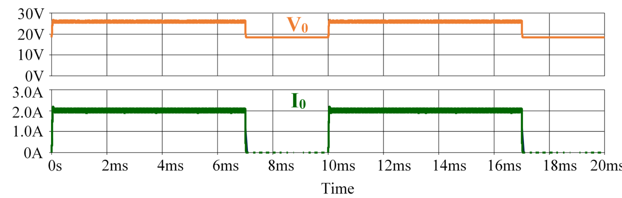
Fig. 8(a) and Fig. 8(b) show LED lamp voltage and current at 50% and 70% of rated illumination respectively. It can be observed that LED voltage and current are maintained at their rated values when inverter is ON and are zero when inverter is OFF, where the required illumination level is achieved based on the average values. At these two illumination levels, efficiency obtained is 85.2% and 86.3% respectively.

VII. Conclusions

A driver circuit using full bridge series resonant converter cascaded with buck-boost converter is proposed to drive LEDs in this study. Inverter switches are operated with constant duty cycle with constant frequency. Thus, the advantages achieved are proper ZVS across the switches at wide range of input variations and simple design of series resonant converter elements. Buck-boost converter is utilized for LED current regulation. The power processed by buck-boost converter is also less, thereby reducing the losses in it. PWM dimming



(a)



(b)

Fig. 8. Simulation waveforms of LED voltage and current at : (a) 50% dimming (b) 70% dimming

is also incorporated in this configuration. This topology is suitable for PV or battery operated applications.

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