An Efficient Parallel Resonant Converter for LED Lighting

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***Abstract*-An LED driver is presented using parallel loaded resonant converter. Output voltage of this converter added to a dc source to feed the lamp load. One voltage source supplies majority of lamp power directly and other supplies a small power through parallel resonant converter for regulation. This driver features zero voltage switching (ZVS), high efficiency and simple control. Illumination control is incorporated using PWM dimming. A 26 W prototype has been developed to confirm its validity.**

Key Words: Parallel resonant converter, LED driver, PWM dimming.

I. INTRODUCTION

Illumination systems utilize considerable portion of total electrical energy generated [1]. Therefore, these system should provide efficient light output to reduce energy expenses. LED lighting is becoming popular. This is owing to the factors like long life, significant luminous efficiency, compactness, etc. [2]. Applications of LEDs cover wide range like traffic lighting, street lighting, LCD back lighting, domestic lighting, automotive lighting, parking lighting and so on [3].

Level of illumination is dependent on the forward current of LED. It needs to be controlled for constant illumination against the variations of source. Therefore LEDs are powered by constant current switching regulators [4]. To suit various operating conditions, variety of drivers has been designed. They Include AC-DC drivers [5], [6], DC-DC drivers [7], [8]. Soft switching techniques help in increasing driver efficiency. It also helps in operating at higher switching frequency for reduction in size of LED driver system.

This study proposes full-bridge configuration based on parallel resonance for LED applications. Two dc voltages in series supply required DC voltage and forward current to the LED load. As the parallel resonant converter processes small power, conduction losses are small. In addition, it offers zero voltage switching. This work is structured as follows. Proposed configuration is described in section II. Operating principle and analysis of the presented system is explained in section III. Dimming feature is explained in section IV. Design guidelines are applied in section V. Simulation results are discussed in VI. Finally, section VII concludes the paper.

II. PROPOSED CONFIGURATION

Fig. 1 displays the proposed LED driver. An H-bridge parallel resonant inverter and diode bridge rectifier are present in the driver circuit. Four power MOSFETs S_1, S_2, S_3 and S_4 form full-bridge inverter. Diode bridge rectifier is formed by four power diodes $D_1 - D_4$. Inductor L_r, capacitor C_r and diode bridge rectifier form parallel resonant circuit. Two voltages V_1 and V_2 are connected in series with LED lamp. Majority of lamp power is processed directly by V_1. Remaining power for control is provided by V_2. The output inductor L_0 makes lamp current I_0 with negligible ripple.

III. OPERATING PRINCIPLE

A. Converter Operation

The H-bridge inverter is operated at fixed frequency with symmetric duty cycle control. Fig. 2 displays the relevant waveforms of converter system. The switches in bridge generate a square wave voltage V_{AB}. This voltage is applied to parallel resonant circuit which produces a sinusoidal voltage V_{CB} across C_r. Voltage V_{CB} is rectified and filtered to produce a current I_0. This current I_0 is reflected across the bridge rectifier input current as i_b. The current $i_b = +I_0$ if V_{CB} is positive and $i_b = -I_0$ if V_{CB} is negative. In the output stage, sum of V_2 which is a full wave rectified voltage of V_{CB} and dc voltage V_1 is applied to series combination of L_0 and LED lamp. Inductor L_0 provides continuous current through LED lamp.

The features of proposed LED driver are given as follows:
1) Operating frequency is constant which reduces electro-magnetic interference (EMI).
2) Duty cycle control is used to regulate lamp current.
3) Efficiency is high due to less processing power.
4) Illumination control is implemented using low frequency modulation of the gating pulses.

B. Converter Analysis

Assumptions made in the converter analysis are presented below:
a) Steady state operation of the converter considered.
b) The power MOSFETs and power diodes used are ideal.
c) The current through LED lamp is constant.

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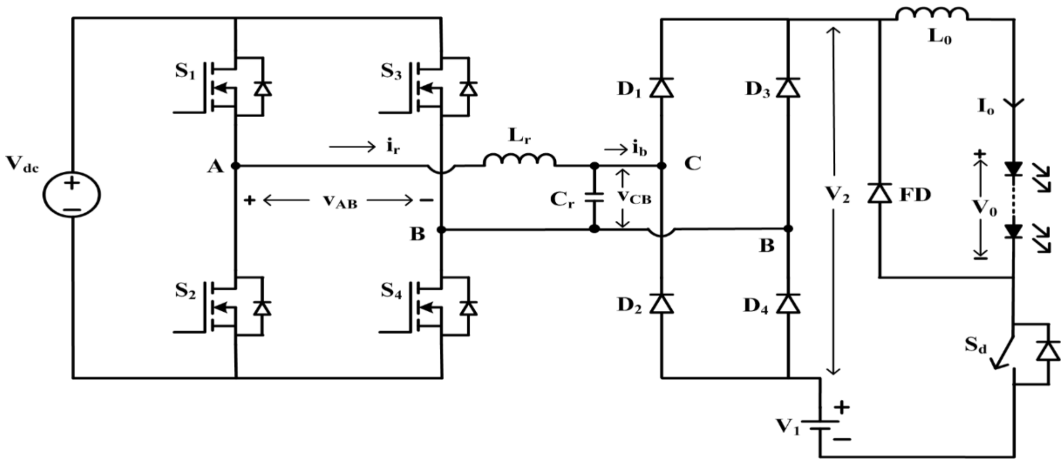


Fig. 1. Proposed LED driver

In the proposed configuration, a square wave voltage of magnitude V_{dc} is generated through switching action. And it is applied to $L_r - C_r$ network that allows fundamental components. Therefore 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. (a). The $L_r - C_r$ network filters all the harmonic voltage components except fundamental component present in the voltage V_{AB}. The ac resistance R_{ac}, which is used in ac equivalent circuit, accounts for the non-linearity present in rectifier. The reactance offered by L_r and C_r are denoted as X_{Lr} and X_{Cr} respectively. From the equivalent circuit shown in Fig. 3. (a), static gain of the proposed driver is represented by using simple voltage division principle:

$$\frac{V_{CB}}{V_{AB}} = \frac{1}{1 - \frac{X_{Lr}}{X_{Cr}} + j\frac{X_{Lr}}{R_{ac}}} \tag{1}$$

Note that V_{AB} is the fundamental component of the square wave voltage applied to $L_r - C_r$ network and V_{CB} is the voltage across R_{ac}. The static gain in terms of actual proposed LED driver values is given by

$$\frac{V_o - V_1}{V_{dc}} = \frac{8}{\pi^2}\left[\frac{1}{1 - \frac{X_{Lr}}{X_{Cr}} + j\frac{X_{Lr}}{R_{ac}}}\right] \tag{2}$$

The ac resistance R_{ac} is calculated by using the circuit shown in Fig. 3. (b) in which the resistance offered by LED lamp and voltage source V_1 is represented as R_{eff}. The R_{ac} is given by

$$R_{ac} = \frac{V_{CB}(rms)}{I_b(rms)} = \frac{\pi V_0}{2\sqrt{2}} \Big/ \frac{4I_0}{\sqrt{2}\pi} = \frac{\pi^2}{8} R_{eff} \tag{3}$$

And, $X_{Lr} = 2\pi f_s L_r$ (4)

$$X_{Cr} = \frac{1}{2\pi f_s C_r} \tag{5}$$

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

$$Q = \frac{R_{eff}}{\omega_0 L_r} \tag{6}$$

Where ω_0 is resonant frequency and it is given by

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{L_r C_r}} \tag{7}$$

By substituting Eqn. (3), (4), (5), (6) and (7) in Eqn. (2), the gain is finally expressed as

$$\frac{V_o - V_1}{V_{dc}} = \frac{1}{\frac{\pi^2}{8}\left[1 - \left(\frac{f_s}{f_0}\right)^2\right] + j\frac{f_s}{f_0}\left(\frac{1}{Q}\right)} \tag{8}$$

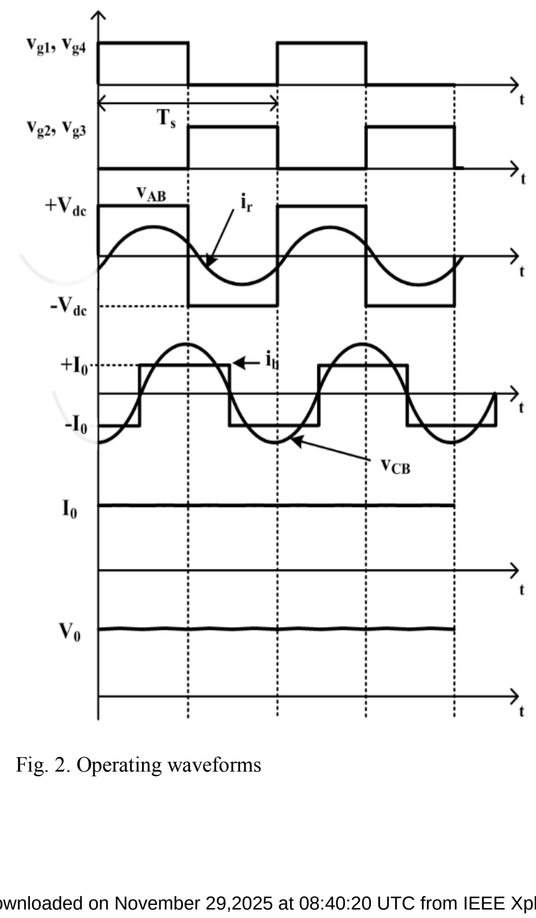


Fig. 2. Operating waveforms

IV. REGULATION OF LED CURRENT AND DIMMING CONTROL

In the proposed configuration devices in H-bridge inverter are operated at constant duty cycle. Therefore LED lamp brightness must be regulated against variations in dc voltages V_{dc} and V_1. To achieve LED lamp current regulation against variations in V_{dc} and V_1, phase-modulation control is used. In this control, magnitude of V_{AB} is regulated by introducing a phase (α) between the switch gate signals of first leg and second leg as shown in fig. 4. (a). The Fourier analysis of V_{AB} gives the following equations:

$$v_{AB} = \frac{4V_{dc}}{n\pi}\cos\left(\frac{n\alpha}{2}\right)\sin(n\omega t)\,, \tag{9}$$

Where n = 1, 3, 5, 7………

Since the fundamental voltage is allowed, its magnitude is given as

$$V_{AB,5} = \frac{4V_{dc}}{\pi}\cos\left(\frac{\alpha}{2}\right) \tag{10}$$

By substituting Eqn. (10) in Eqn. (8), the static gain of the parallel resonant converter is

$$\frac{V_o - V_1}{V_{dc}} = \frac{\cos\left(\frac{\alpha}{2}\right)}{\frac{\pi^2}{8}\left[1-\left(\frac{f_s}{f_0}\right)^2\right] + j\frac{f_s}{f_0}\left(\frac{1}{Q}\right)} \tag{11}$$

The magnitude of square wave voltage applied to $L_r - C_r$ network can be found by using Eqn. (11) after selecting the LED load, switching frequency and resonant frequency. And the variations in V_{dc} and V_1 are compensated by adjusting the phase (α).

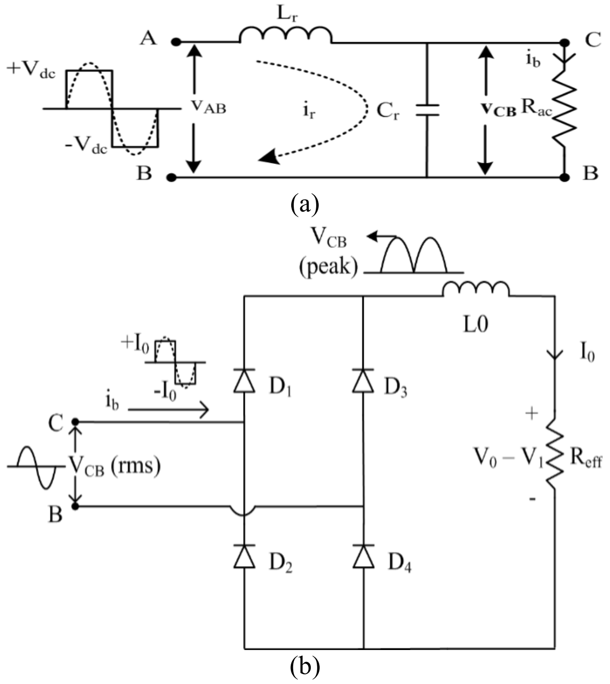


Fig. 3. (a) AC equivalent circuit (b) Equivalent circuit for R_{ac}

To save good amount of power, LED driver must provide adjustable illumination which is an essential feature for LED applications. In the literature, many techniques have been reported for dimming operation, such as stated like: amplitude modulation (AM) [9], pulse width modulation (PWM) [8], double pulse width modulation [10], bi-level current control [11], on-off control [12], etc. In the proposed study, PWM dimming is incorporated by connecting a switch S_d in series with LED lamp. It turns on and off the LED lamp at operating current by dimming signal at low frequency V_{gd}. Thus LED current is controlled in an average sense. The dimming signal, voltage V_{AB}, LED lamp voltage and current are shown in Fig. 4. (b).

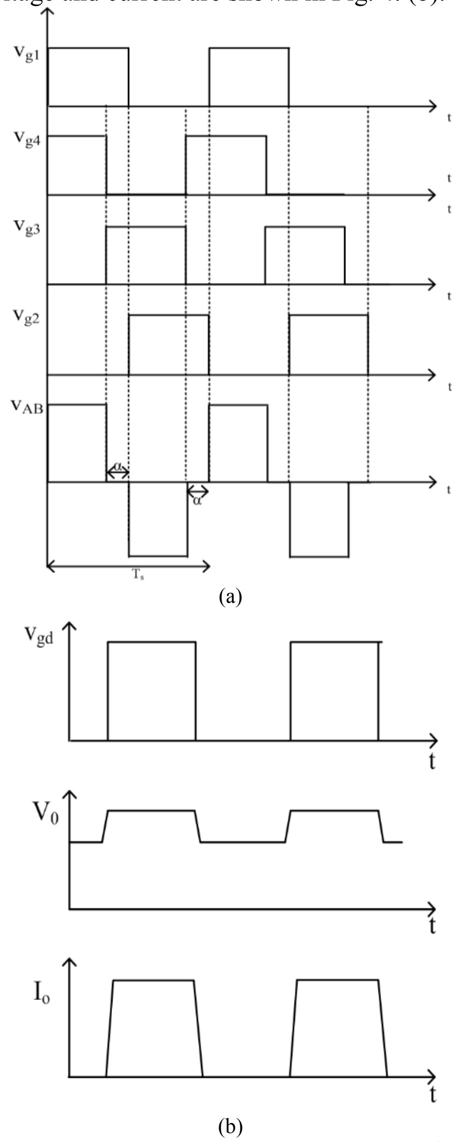


Fig. 4. (a) Gate pulses and output voltage (b) Gate signal of dimming switch, LED lamp current and voltage

V. GUIDELINES FOR DESIGN

Based on load (LED) circuit values, inverter and rectifier system are designed. LED load is taken as series combination of a cut-in or threshold voltage Vth, a dynamic resistance rd and an ideal diode [13]. In the presented circuit, load consist of 16 LEDs in series. The forward drop of each LED is 3.25 V, at 510 mA. And the cut-in voltage of each LED is 2.32 V. Therefore LED lamp has a total cut-in voltage of 37.2 V, a total operating voltage of 52 V, and a current of 510mA. Consequently power consumed by lamp is 26 W.

A. Calculation of L_r and C_r:

The product of L_r and C_r is obtained from Eqn. (7) and it is expressed as

$$L_r C_r = \left[\frac{1}{2\pi f_0}\right]^2 \tag{12}$$

After selecting resonant frequency f_0 as 180 kHz, Eqn. (12) is expressed as

$$L_r C_r = 0.782 \times 10^{-12} \tag{13}$$

From Eqn. (13), the inductor L_r and capacitor C_r are selected as 15.64 µH and 0.05 µF respectively.

B. Selection of input dc voltage V_1 and V_{dc}:

As it has been discussed that load voltage V_0 is the sum of dc voltages V_1 and V_2.To increase the overall efficiency, V_1 should be greater than V_o. Therefore V_1 is selected as 48V. Remaining 4V is the dc voltage V_2. From Eqn. (11), the input voltage is calculated as 12V.

C. Selection of output inductor L_0:

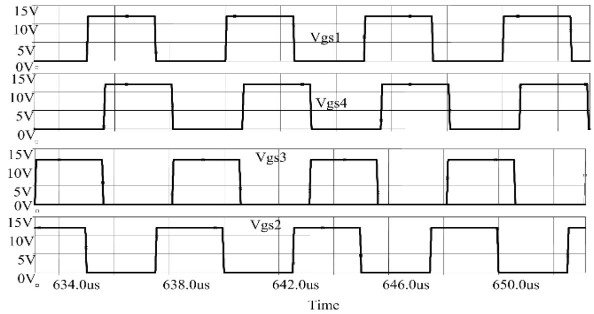
To limit the LED lamp current ripple within 10% of its average value, a value of 250µH is selected. As there is no electrolytic capacitor, the reliability presented circuit is more.

Table A	Specifications of the presented circuit
Supply voltage, V_{dc}	12 V
Auxiliary source, V_1	48 V
Number of LEDs	16
V_0	52
I_0	510 mA
P_0	26 W
Switching frequency, f_s	200 kHz
Resonant frequency, f_0	180 kHz
L_r	15.64 µH
C_r	0.05 µF
L_0	250 µH
PWM dimming frequency	100 Hz
Power MOSFETs	IRF640N
Power diodes	MUR 460

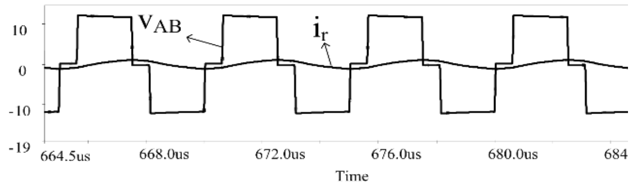
VI SIMULATION RESULTS

The presented system is simulated for 26 watts output power. Table A gives the specifications of the designed LED system. Fig. 5 displays the control signals of devices in H-bridge inverter with phase shift control, inverter output voltage, resonant current, LED lamp voltage and current. Fig. 6 displays the voltage across resonant capacitor and lamp current. Small ripple present in load current is 4% of selected operating current. Since the converter is processed small power, associated losses are reduced.

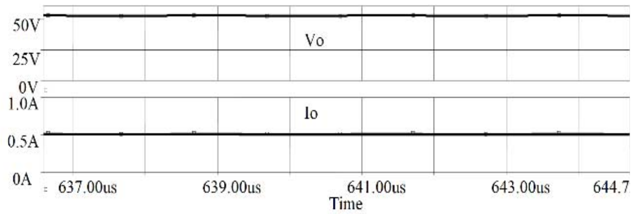
Fig. 7 shows LED lamp voltage and current at 50% of rated illumination. It can be noticed that during dimming LED current remains at either rated value or zero. Thus average load current is controlled.



(a)

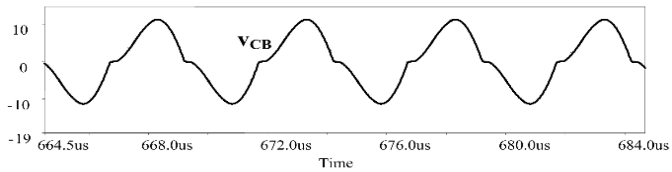


(b)

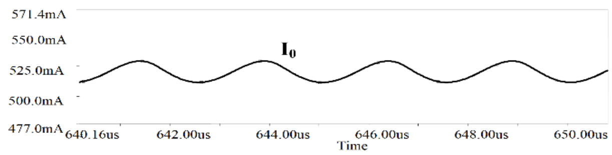


(c)

Fig. 5. (a) Control signals of inverter (b) Inverter output voltage and resonant current (c) LED lamp voltage and current



(a)



(b)

Fig. 6. (a) Voltage across C_r (b) LED lamp current

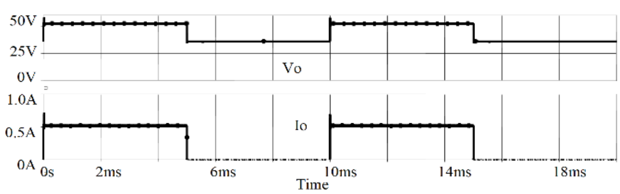


Fig. 7. LED lamp voltage and current at 50% dimming

VII CONCLUSIONS

A full bridge converter using parallel resonance is proposed to drive Light Emitting Diodes (LEDs) in this study. LED lamp is powered by two dc voltages which are in series. One supplies majority of power directly and other processes small power through converter. As the conversion power is less, associated losses have small impact on overall efficiency. LED lamp current is regulated by using phase-shift control. Pulse-width modulation (PWM) dimming is also incorporated in this configuration. This topology is suitable for battery operated and low voltage dc applications.

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