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Reduced Ripple Current LED Lighting System with Two Series Resonant Converters

V K Satyakar Veeramallu
Department of Electrical Engineering
National Institute of Technology
Warangal, India

S Porpandiselvi
Department of Electrical Engineering
National Institute of Technology
Warangal, India
Email:porpandiselvi@gmail.com

B L Narasimharaju
Department of Electrical Engineering
National Institute of Technology
Warangal, India

***Abstract*— In this paper, a full-bridge series resonant converter based LED driver is proposed. Phase shift control is employed for regulating LED current. Here two full-bridge series resonant converters are operated in phase shift in order to reduce LED current ripple. With reduced ripple current it offers the advantage of avoiding electrolytic capacitor increasing the life span of LED driver. ZVS is incorporated in this proposed converter and hence switching losses are reduced. It regulates LED current against input voltage variation. The detailed description, circuit analysis and simulation results of the proposed converter are presented.**

Keywords—LED driver, phase shift control, ZVS operation

I. Introduction

Nowadays, due to the outstanding features, High brightness light emitting diode (HB-LED) is the best solution in lighting applications. They have features like high operating life, high luminous efficiency with compact in size. LEDs are generally driven from AC or DC source using AC-DC or DC-DC converters. For small lighting applications DC supply from batteries can be used as power supply. Switch mode power supplies due to their high efficiency, are generally used as DC-DC converters [1]. LEDS generally have life span of more than 50,000 hours [2]. The classical converters like buck, boost, buck-boost when used for lighting applications have limited life as they use electrolytic capacitors whose life span is nearly 10,000 hours for limiting high ripple content [3]. Therefore there is a requirement of high efficient LED drivers which can reduce the ripple current, thus avoiding the electrolytic capacitors.

In [4], interleaved buck converter based LED driver is discussed, where the ripple can be still improved. Zero current switching (ZCS) incorporated LED driver is discussed in [5]. In [6] class-D resonant converter with ZVS is employed for LED lighting application. Half bridge and full bridge converters can be employed for lighting applications. When compared with half bridge, full bridge converter has advantage of handling higher power. In [7], full bridge based resonant converters are used for LED driver applications. ZVS can be achieved in these converters by using LC series resonance thereby reducing switching losses. In [8], LED driver using AC-DC converter is presented in series with buck converter as ripple cancellation circuit for cancelling double frequency ripple. In [9] flyback based AC-DC converter is used along with bidirectional buck-boost converter in parallel for double frequency ripple cancellation in LED current.

This paper proposes an LED driver using two Full-bridge phase modulation controlled LC series resonant converters in parallel for minimization of LED ripple. Soft switching is employed in proposed converter, thereby reducing switching losses. Full bridge resonant converter is controlled using phase modulated control, thereby regulating LED current. Ripple content in LED current is reduced by connecting two full bridge resonant converters operated with 90^{o} phase shift. This proposed converter eliminates electrolytic capacitor by reducing the ripple content to a considerable value. Line regulation is also possible using the proposed converter. Principle of operation of the proposed circuit is explained in section II. Analysis of proposed LED driver is discussed in section III. In section IV, design procedure is described. In section V, Section VI states the conclusions of the proposed LED driver.

II. PRINCIPLE OF OPERATION

The proposed phase modulated full bridge LC series resonant converter based topology is shown in Fig.1. The circuit consists of two full bridge inverters with switches S_1, S_2, S_3, S_4, S_1', S_2', S_3' and S_4'. The output of each inverter drives series LC resonant network. The tank current is rectified by a full bridge diode rectifier. The two rectifier outputs are connected across LED load and small filtering capacitor, C_o.

Generally LED load is driven by using a single full bridge resonant converter. A DC voltage is applied across full bridge inverter which is operated at high switching frequency, f_s. A square wave voltage is generated at the output of full bridge inverter. This square wave when applied across series LC resonant circuit by selecting the switching frequency, f_s higher than the resonant frequency, f_r ZVS is achieved. This will reduce switching losses and therefore efficiency increases. The current flowing in the resonant tank is nearly sinusoidal in nature. This sinusoidal current is rectified using full bridge diode rectifier and applied across LED load with filter capacitor. But the ripple content in the LED load is more and the electrolytic capacitors are need to reduce the ripple which reduces the life span of LED driver. In the proposed topology two such full bridge resonant converters are used. Rectified

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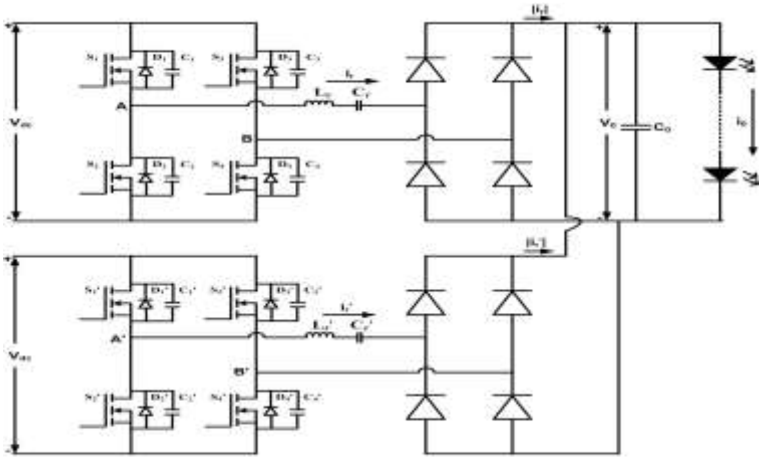


Fig. 1 Proposed LED driver

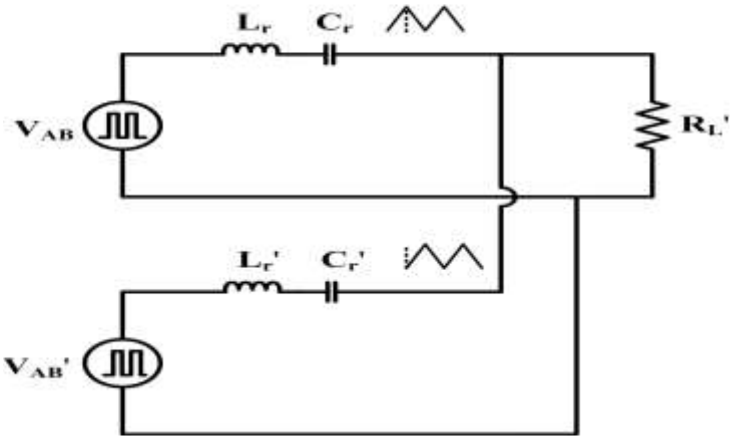


Fig. 2. Equivalent circuit of Proposed Converter

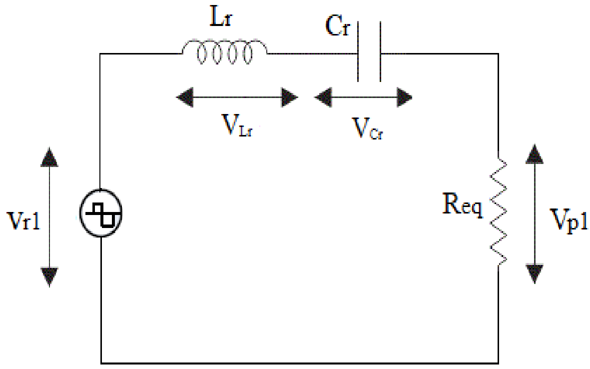


Fig. 3. AC Equivalent circuit of Series Resonant Converter

tank currents of the two inverters are connected in parallel. The two inverters are operated with 90° phase shift. Hence when the two rectified currents are added, it results in considerable ripple cancellation. Hence the capacitor needed at the output of the rectifiers i.e., across the load is very small. Hence this capacitor need not be electrolytic. This increases the life of the LED driver. In order to have better current ripple cancellation, the current produced in the LC resonant tank is made as triangle in nature by increasing f_s compared to f_r. Thereby the rectified triangle currents have maximum ripple cancellation and thus current with less ripple flows in the LED load. As the ripple current is reduced less than 10% electrolytic capacitors can be avoided. Instead small capacitors can be used to reduce the small ripple. The LED forward current is regulated using phase shift control of full bridge series resonant converters against supply voltage variations.

III. CIRCUIT ANALYSIS

The analysis of the proposed LED driver is done by considering one full bridge series LC resonant converter and the same analysis can be carried to second full bridge series LC resonant converter. The following assumptions are considered

(i) The proposed converter is operating in steady state

(ii) The circuit components are ideal

Fig. 4 shows LED equivalent circuit. It consists of a series combination of threshold voltage V_{th}, internal resistance of LED R_{LED} and an ideal diode.

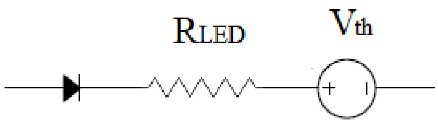


Fig. 4 LED Equivalent Circuit

The square wave voltage generated from full bridge inverter is applied across the series LC resonant tank circuit. The AC equivalent circuit of LC resonant tank obtained by Fundamental Component Analysis method is shown in Fig. 3 where V_{r1} is the fundamental voltage of input voltage for resonance network, V_{o1} is fundamental output voltage across output filter capacitor, C_o and R_{eq} is the equivalent load resistance.

The fundamental components V_{r1}, V_{o1} and R_{eq} can be expressed as

$$V_{r1} = \frac{4V_{dc}}{\pi} \tag{1}$$

$$V_{o1} = \frac{4V_o}{\pi} \quad (2)$$

$$R_{eq} = \frac{\pi^2}{8} R_L' \quad (3)$$

where $R_L' = V_o/I_o$

From Fig. 3, the DC voltage conversion ratio equation of LC series-resonant converter in the ideal condition is obtained as below

$$\frac{V_{o1}}{V_{r1}} = \frac{1}{\sqrt{1+\left[\left(X_L - X_C\right)/R_{eq}\right]^2}} \quad (4)$$

where reactances X_L and X_C are

$$X_L = \omega_s L_r \quad (5)$$

$$X_C = 1/\omega_s C_r \quad (6)$$

$$\omega_s = 2\pi f_s \quad (7)$$

The quality factor, Q of the LC series resonant converter is given as

$$Q = \frac{\omega_s L_r}{R_{eq}} = \frac{1}{\omega_s R_{eq} C_r} \quad (8)$$

By substituting Eqns. (1), (2), in (4), we get the voltage gain at steady state as expressed below

$$\frac{V_o}{V_{dc}} = \frac{1}{\sqrt{1+\left[\left(X_L - X_C\right)/R_{eq}\right]^2}} \quad (9)$$

which indicates that the output voltage depends on switching frequency, ω_s.

By substituting equations 5, 6, 8 in 9, we get

$$\frac{V_o}{V_{dc}} = \frac{1}{1+Q^2\left[\left(\omega_s/\omega_r\right)-\left(\omega_r/\omega_s\right)\right]^2} \quad (10)$$

Fig. 5 shows the gate pulses, tank voltage (V_{AB}/V_r), tank current (i_r) of the proposed converter.

Fig. 6 shows the graph plotted between gain Vo/V_{dc} and normalized angular frequency for various values of Q.

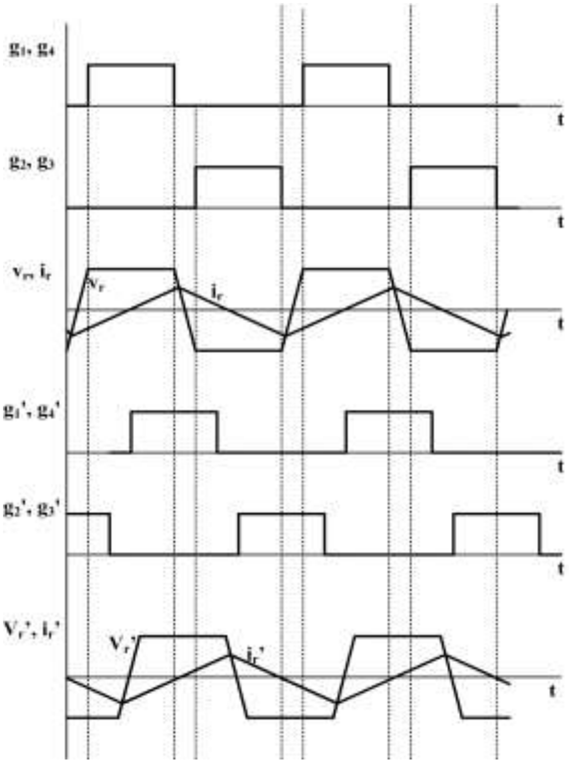


Fig. 5 Operating waveforms

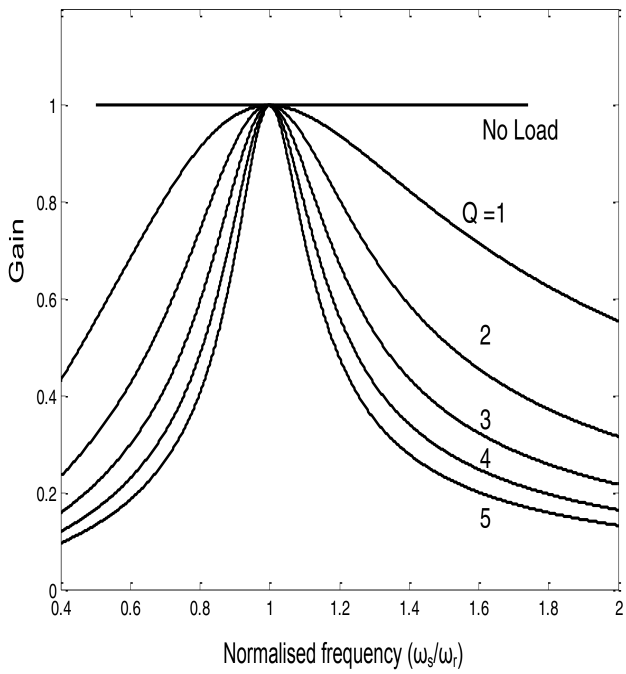
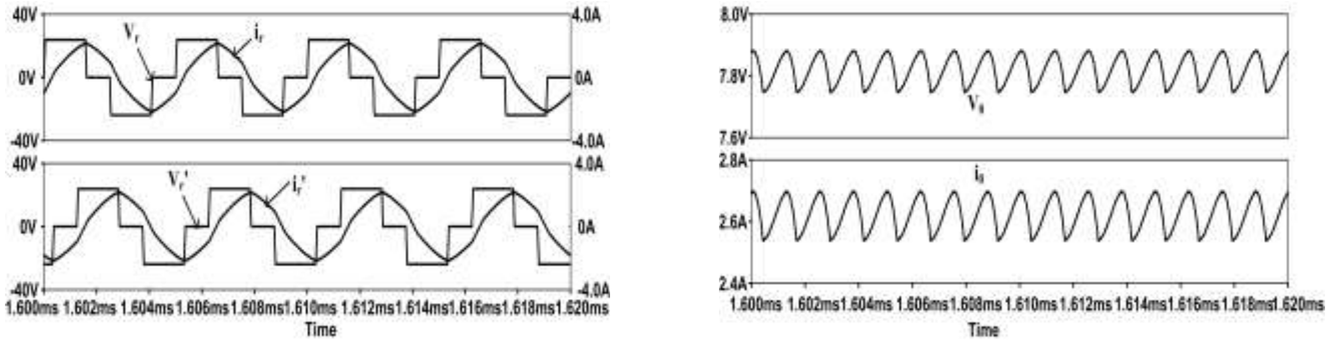


Fig. 6 Graph between normalized angular frequency and voltage gain V_0/V_{dc} for various values of Q



a

b

Fig. 7 Simulation waveforms at nominal voltage (Duty Ratio = 65%)
(a) Tank voltages and tank currents
(b) LED voltage and LED current

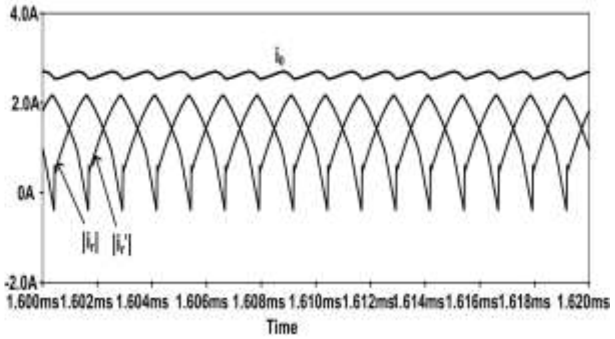


Fig. 8 Simulation waveforms of LED current, rectified currents of both bridges at nominal voltage (Duty Ratio = 65%)

Table 1 Parameters of proposed LED driver	
DC voltage, V_{dc}	24 V
Output Voltage	7.22 V
Rated Power	23.826W
Number of parallel strings	6
Number of LEDs used in each parallel string	2
LED operating current, i_{LED}	550 mA
Switching frequency, f_s	200 kHz
Duty ratio of switches in bridge configuration	0.65
L_r	15 µH
C_r	100 nF
C_0	0.94 µF
Resonant frequency, f_r	130 kHz

IV. DESIGN CONSIDERATIONS

In the proposed work LED load contains six parallel strings of LEDs. Each string contains two LEDs connected in series. Each LED is operated at 3.61 V, 550 mA and 1.9855 W. Thereby LED lamp is operated at 7.22 V, 3.3 A and 23.826 W.

The LED load current is the obtained from addition of two resonant converters with reduced ripple, given by the equation below.

$$i_o = |i_r| + |i_r'| \tag{11}$$

The components used for both the converters are same except that both the converters are operated in a 90° phase shifted manner. Hence design parameters will be discussed for single converter and same implies for the second converter.

The switching frequency is chosen as 200 kHz. For f_s/f_r ratio of 1.53, resonant frequency (f_r) of the converter is calculated as

$$f_r = \frac{f_s}{1.53} = 130 \text{ kHz}$$

The relation between f_r, L_r and C_r is given by

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{12}$$

The value of capacitance (C_r) is taken as 100nF. A current magnitude is required to charge and discharge output capacitors of switches S_1 and S_2 during dead time to ensure ZVS. The inductance L_r provides the same.

Rearranging Eqn. (12)

$$L_r = \frac{1}{(2\pi f_r)^2 C_r} \tag{13}$$

L_r is calculated as 15µH.

V. SIMULATION RESULTS

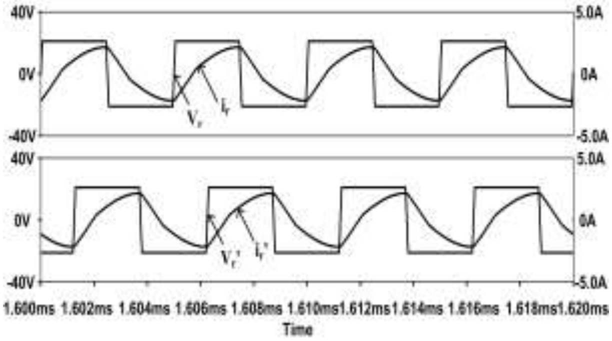
The proposed converter has been simulated in ORCAD PSpice software. The circuit parameters of the converter are listed in Table 1. The DC input voltage for each bridge, V_{dc} is chosen as 24V.

The proposed converter can be operated from batteries. The operation of the proposed converter is studied for two conditions; one for nominal input voltage condition and under input voltage variations that may be due to battery discharge conditions. Fig. 7, 8 shows the corresponding waveforms under nominal voltage conditions. Fig. 9, 10 shows the corresponding waveforms considering battery discharge conditions.

The required output voltage for a rated current of 3.3 A is 7.22 V. At nominal voltage of V_{dc} = 24 V, the required voltage is obtained at a duty ratio of 65% and during battery discharge condition of 12.5 % i.e., for V_{dc}=21 V, the required voltage is obtained at full square wave (duty ratio = 100 %). The current in LED can be regulated by varying the duty ratio of both the converters simultaneously for any variations in supply voltage. The output capacitor C_0 is chosen as 0.94 µF such that both voltage and current ripples are in their specified limits.

Fig. 7a shows simulation waveforms of tank voltage and tank current for a duty ratio of 65 %. Fig. 7b represents the LED voltage and lamp current waveforms under nominal voltage condition for a duty ratio of 65 %. Fig. 8 shows the rectified current waveforms of both the converters. The negative current in both the rectified currents is due to the reverse recovery current of the diodes. The current cancellation of both the currents will occur as they are phase shifted by 90° . Thereby decreasing current ripple in the load as shown in Fig 8. A voltage ripple of around 1.67 % and a ripple in current of 6.01% is observed.

Fig. 9a shows simulation waveforms of tank voltage and tank current for a duty ratio of 100 %. Fig. 9b represents the LED voltage and lamp current waveforms during discharge condition for a duty ratio of 100 %. Fig.10 shows the rectified current waveforms of both the converters. The voltage ripple and current ripple under this condition is observed to be nearly same i.e., 2.8 % and 9.8 % respectively.



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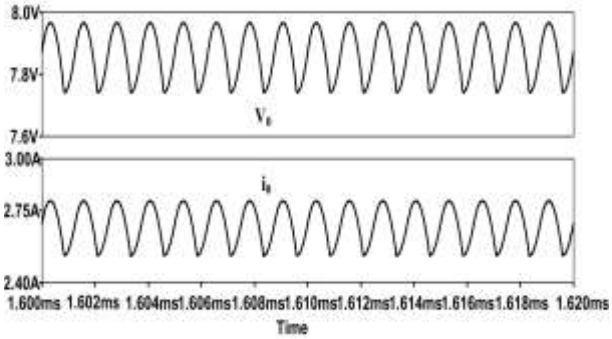

b

Fig. 9 Simulation waveforms during discharge condition (Duty Ratio = 100%)
(a) Tank voltages and tank currents
(b) LED voltage and LED current

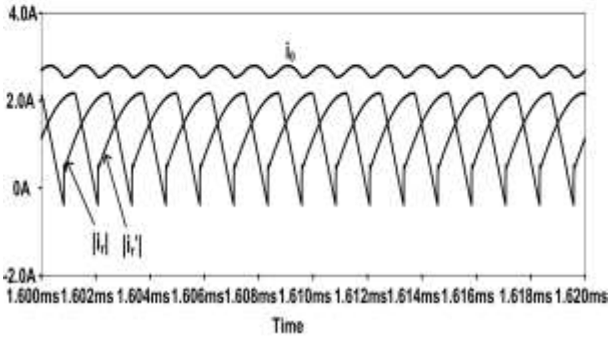

Fig. 10 Simulation waveforms of LED current, rectified currents of both bridges during discharge condition (Duty Ratio = 100%)

VI. CONCLUSION

A phase modulated full-bridge series resonant converter based LED driver for lighting application is proposed in this paper. Two full-bridge series resonant converters are operated in 90° phase shift in order to reduce LED current ripple. Thereby the proposed converter eliminates use of electrolytic capacitor increasing the life span of LED driver. ZVS is achieved in the proposed converter using series LC resonant circuit. Therefore switching losses are reduced increasing converter efficiency. The LED current is regulated using phase shift control method for any input voltage variations.

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