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Reduced Ripple Current Three phase Parallel Loaded Resonant Converter for LED Lighting

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***Abstract*— In this paper, a three phase full-bridge parallel loaded LC resonance converter based DC-DC LED driver is proposed for LED lighting applications. This converter reduces the ripple content to a very low value such that filter capacitor can be eliminated. This increases the lifespan of the LED driver. The filter inductor used is very small as the ripple content is reduced and ripple frequency is increased. ZVS is achieved in the proposed converter using parallel loaded LC resonance by which switching losses are minimized and efficiency of the converter is increased. Dimming is also employed in the proposed converter. LED current is controlled by varying switching frequency of the converter for supply voltage variations. The detailed description, circuit analysis and simulation results of the proposed converter are presented.**

Keywords—LED driver, three phase full bridge, ZVS operation

I. INTRODUCTION

Now-a-days, high brightness light emitting diode (HB-LED) become popular choice for lighting applications due to their remarkable advantages. They owe features like high luminous efficacy, long operating life, compact size. Power electronic drivers are generally employed as an interface between LED load and power supply. Power supply can be either DC or AC. For low power levels, DC supply from battery is a common choice. DC-DC converters are commonly used as they are highly efficient [1]. LEDS generally have life span of more than 50,000 hours [2]. The classical converters based on buck, boost, buck-boost have high voltage ripple, thereby use electrolytic capacitors for reducing ripple. The electrolytic capacitors have reduced life span of 10,000 hours [3]. Therefore these converters when employed for LED lighting applications reduces overall life span of LED drivers. As LEDs have high efficiency, the design of driver circuit also affects overall efficiency. Dimming is generally employed in LED drivers for controlling illumination of LEDs and for energy saving. LED drivers should possess a simple built in dimming feature. To fulfill above requirements advanced technology DC-DC converter based LED drivers are required.

In [4], a non-isolated two channel LED driver is proposed, where the ripple is reduced by using 90° phase shift. Soft switching like Zero voltage switching (ZVS), Zero Current switching (ZCS) can be employed in the LED drivers for reducing the switching losses. ZVS or ZCS can be achieved in the LED drivers by using resonant converters as DC-DC converters. Zero current switching (ZCS) incorporated LED driver is discussed in [5]. In [6] class-D resonant converter with ZVS is used as LED driver. In [7], single phase full bridge based resonant converters are used for LED lighting applications. DC voltage rectified from 3-φ AC supply have less ripple (4 %) compared to DC voltage rectified from 1-φ AC supply (48.2 %). Thereby as the ripple reduces, filter capacitor can be eliminated increasing the life span of LED driver. Compared to 1-φ, 3-φ rectifier has output voltage 3 times higher frequency thereby the size of filter components used can be reduced. In [8], three phase resonant switched capacitor based LED driver is proposed using AC source.

In this paper, a three phase full-bridge parallel loaded LC resonant converter based DC-DC LED driver is proposed. LED current is regulated by varying the switching frequency against supply voltage variations. Soft switching is achieved in the proposed converter. Using the three phase topology, ripple current in the LED driver is reduced very much. Thereby the filter capacitor is eliminated increasing the life span of the LED driver. Size of the filter inductor used is also very less. Dimming is also achieved in 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, Dimming Control is discussed. Section VI discusses the simulation results. Section VII states the conclusions of the proposed LED driver.

II. PRINCIPLE OF OPERATION

Fig.1 shows the proposed 3-φ full bridge parallel loaded LC resonance based LED driver. The circuit consists of a three phase square wave inverter with switches S_1 to S_6. Output of the three phase inverter is connected across parallel loaded LC resonance circuit where L_r and C_r being resonance elements. Voltages across resonant capacitors is rectified by using 3-φ diode bridge rectifier. The rectified output is applied to LED load through filter inductor L_o. Dimming is achieved by using switch, S_d in series with the LED load. A freewheeling diode, D_o is used to create freewheeling path for inductor current when dimming is employed.

Here DC voltage, V_{dc} is the input to 3-φ square wave inverter operating at a high switching frequency, f_s (200 kHz). The inverter is operated in 180° mode so that each switch is

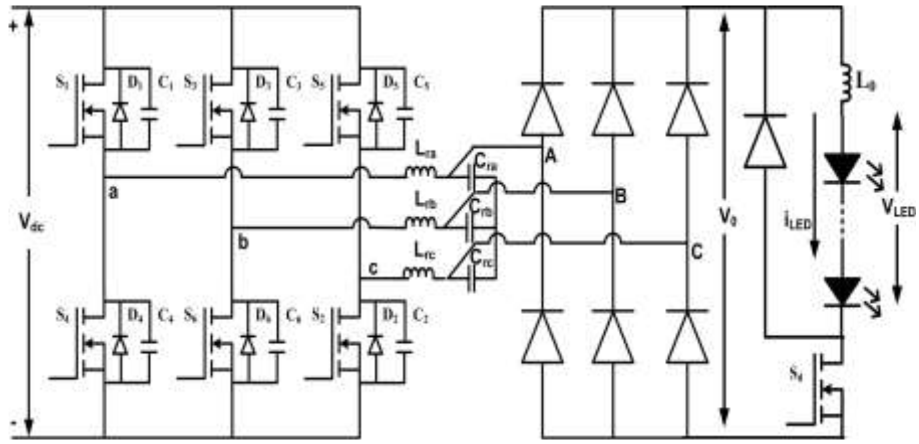


Fig. 1 Proposed LED driver

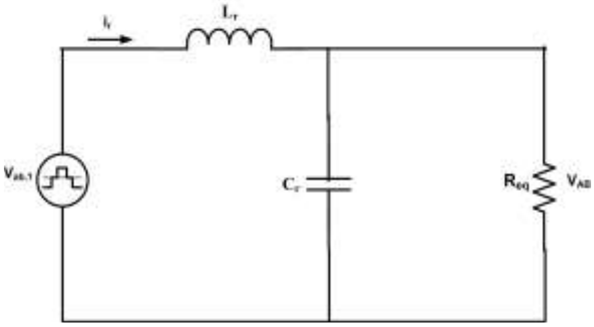


Fig. 2. Per phase equivalent circuit of parallel loaded resonant converter

utilized effectively and output power is higher. The top and bottom switches in each leg are operated complementary to each other. The switching sequence followed is 561, 612, 123, 234, 345 and 456. At any instant three switches are conducting. A square wave voltage is generated at each pole having 120° phase shift from pole to pole. Quasi Square wave voltage is generated in line to line at the output with 120° phase shift between line to line voltages. This square wave output is applied to parallel loaded LC resonant tank which has resonant frequency, $f_r < f_s$. Therefor ZVS is achieved for each switch reducing the switching losses and thereby increasing inverter efficiency. The three phase line to line voltage across resonant capacitors is nearly sinusoidal in nature. This three phase line to line voltage is rectified using three phase diode bridge rectifier. The rectified output voltage will have reduced ripple having frequency 6 times higher than switching frequency. As ripple content is reduced filter capacitor can be eliminated. The ripple in the LED current can be minimized by using a small series inductor. The LED current can be regulated by varying the switching frequency against supply voltage variations. PWM Dimming is employed by operating the dimming switch S_d, with lower frequency. The inductor current is freewheeled through diode D_o when dimming is employed.

III. CIRCUIT ANALYSIS

The analysis of the proposed LED driver is done by considering the following assumptions

(i) The proposed converter is operating in steady state

(ii) The circuit components are ideal

Fig. 3 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.

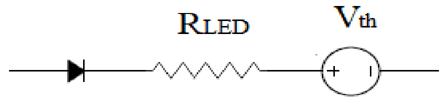


Fig. 3 LED Equivalent Circuit

The square wave voltage generated at the output of 3-φ inverter is applied to the three phase parallel loaded LC resonant tank circuit. The fundamental component analysis is done for the proposed network. Accordingly, here $V_{ab,1}$, $V_{bc,1}$, and $V_{ca,1}$ are the fundamental components of the three line voltages at the output of the inverter. These are the input voltages to the three phase resonant tank. V_{AB}, V_{BC}, and V_{CA} are three rms line voltages obtained from the three resonant capacitors. It is assumed that these voltages are very close to sine waves. R_{eq} is the per phase equivalent load resistance.

The fundamental peak values of input line voltages for LC resonant circuit obtained from 3-φ inverter are expressed as

$$V_{ab,1} = V_{bc,1} = V_{ca,1} = \frac{2\sqrt{3}V_{dc}}{\pi} \tag{1}$$

The fundamental peak values of output line voltages of LC resonant circuit are expressed as

$$V_{AB} = V_{BC} = V_{CA} = \frac{\pi V_o}{3\sqrt{2}} \tag{2}$$

where V_o is the average output voltage of 3-φ rectifier.

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

$$\frac{V_{AB}}{V_{ab,1}} = \frac{1}{\sqrt{\left(1 - \frac{X_{L_r}}{X_{C_r}}\right)^2 + \left(\frac{X_{L_r}}{\mathrm{R}_{eq}}\right)^2}} \tag{3}$$

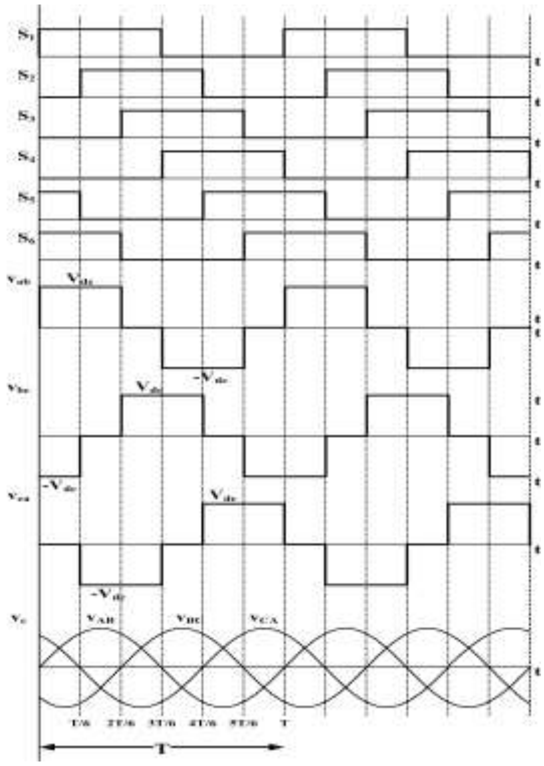


Fig. 4 Operating waveforms

where per phase reactances X_{L_r} and X_{C_r} are

$$X_{L_r} = \omega_s L_r \tag{4}$$

$$X_{C_r} = 1/\omega_s C_r \tag{5}$$

$$\omega_s = 2\pi f_s \tag{6}$$

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

$$Q = \frac{R_{eq}}{\omega_s L_r} = \omega_s R_{eq} C_r \tag{7}$$

By substituting Eqns. (1), (2), in (3), we get the voltage gain at steady state as expressed below

$$\frac{V_o}{V_{dc}} = \frac{6\sqrt{6}}{\pi^2} \frac{1}{\sqrt{\left(1 - \frac{X_{L_r}}{X_{C_r}}\right)^2 + \left(\frac{X_{L_r}}{\mathrm{R}_{eq}}\right)^2}} \tag{8}$$

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

By substituting equations 4, 5, 7 in 8, we get

$$\frac{V_o}{V_{dc}} = \frac{6\sqrt{6}}{\pi^2} \frac{1}{\sqrt{\left(1-k^2\right)^2 + \left(\frac{k}{Q}\right)^2}} \tag{9}$$

where k is the normalized angular frequency, expressed as

$$k = \frac{\omega_s}{\omega_r} \tag{10}$$

Fig. 4 shows the gate pulses, line to line tank voltages (V_{ab}, V_{bc}, V_{ca}), line to line capacitor voltages (V_{AB}, V_{BC}, V_{CA}), tank current (i_r) of the proposed converter.

IV. DESIGN CONSIDERATIONS

In the proposed work LED load contains two parallel strings of LEDs. Each string contains five LEDs connected in series. Each LED is operated at 3.63 V, 550 mA and 1.9965 W. Thereby LED lamp is operated at 18.15 V, 1.1 A and 19.965 W.

The switching frequency is chosen as 210 kHz. For f_s/f_r ratio of 1.21, resonant frequency (f_r) of the converter is calculated as

$$f_r = \frac{f_s}{1.53} = 172.62 \text{ kHz}$$

The relation between f_r, L_r and C_r is given by

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{11}$$

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. (11)

$$L_r = \frac{1}{(2\pi f_r)^2 C_r} \tag{12}$$

L_r is calculated as 8.5 µH.

Here, switching frequency is varied for current regulation if at all any variations in supply voltage. The LED driver can be operated from batteries. Considering a discharge of 12.5 % in input voltage, the switching frequency f_s is varied to 200 kHz thereby f_s/f_r ratio becomes 1.158.

V. DIMMING CONTROL

The brightness of LED can be adjusted by dimming. Commonly used dimming techniques are Amplitude Modulation (AM) and Pulse Width Modulation (PWM) techniques. Among them PWM technique is preferred as flicker goes unnoticeable. The ON and OFF cycles are changed for the purpose of dimming. A switch, S_d is connected in series with the load so as to incorporate dimming in the proposed circuit. A diode D_0 is connected in antiparallel to the combination of inductor L_0 and load so as to provide freewheeling path during dimming. The switch S_d is operated at a frequency of 1 kHz. The switch can be turned ON and OFF at this frequency to adjust the brightness of LED.

Table 1 Parameters of proposed LED driver

DC voltage, V_{dc}	24 V
Output Voltage	18.15 V
Rated Power	20W
Number of parallel strings	2
Number of LEDs used in each parallel string	5
LED operating current, i_{LED}	1.1 A
Switching frequency, f_s	210 kHz
Duty ratio of switches in a single leg	0.5
L_r	8.5 µH
C_r	100 nF
PWM dimming frequency	1 kHz
Duty ratio of dimming switches S_d	0 to 1
L_0	10 µH
Resonant frequency, f_r	172.62 kHz

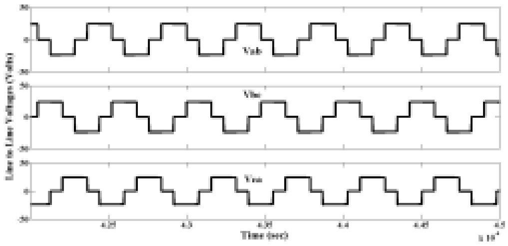


Fig. 5 Line to Line tank voltages (V_{ab}, V_{bc}, V_{ca}) under nominal voltage condition (f_s=210 kHz)

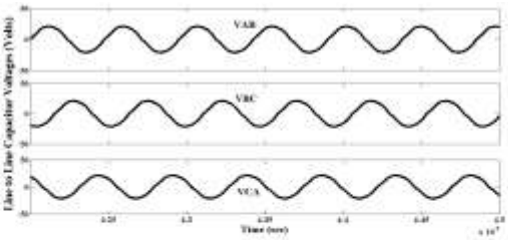


Fig. 6 Line to Line capacitor voltages (V_{AB}, V_{BC}, V_{CA}) under nominal voltage condition (f_s=210 kHz)

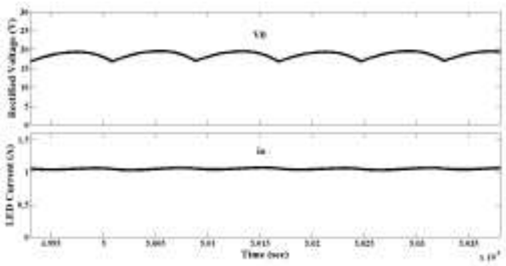


Fig. 7 Rectified Voltage V_0 and LED current i_0 under nominal voltage condition (f_s=210 kHz)

VI. 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 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. 5, 6, 7, shows the corresponding waveforms under nominal voltage conditions. Fig. 8, 9, 10 shows the corresponding waveforms considering battery discharge conditions.

The required output voltage for a rated current of 1.1 A is 18.15 V. At nominal voltage of V_{dc} = 24 V, the required voltage is obtained at a frequency of 210 kHz and during battery discharge condition of 12.5 % i.e., for V_{dc}=21 V, the

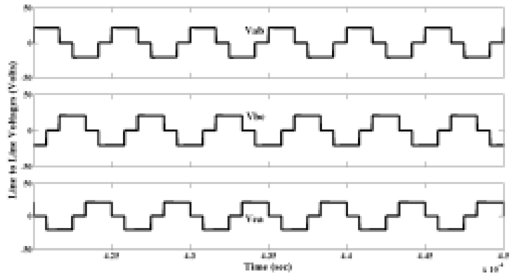


Fig. 8 Line to Line tank voltages (V_{ab}, V_{bc}, V_{ca}) under discharge condition (f_s=200 kHz)

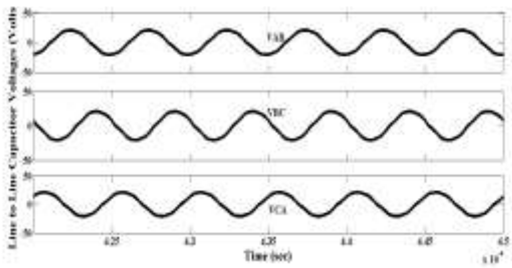


Fig. 9 Line to Line capacitor voltages (V_{AB}, V_{BC}, V_{CA}) under discharge condition (f_s=200 kHz)

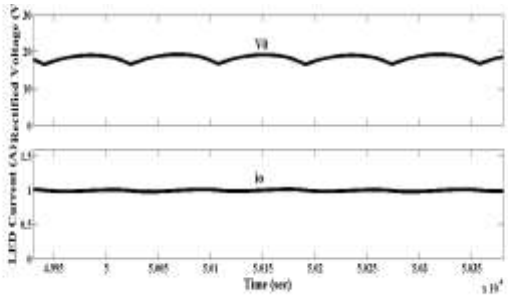
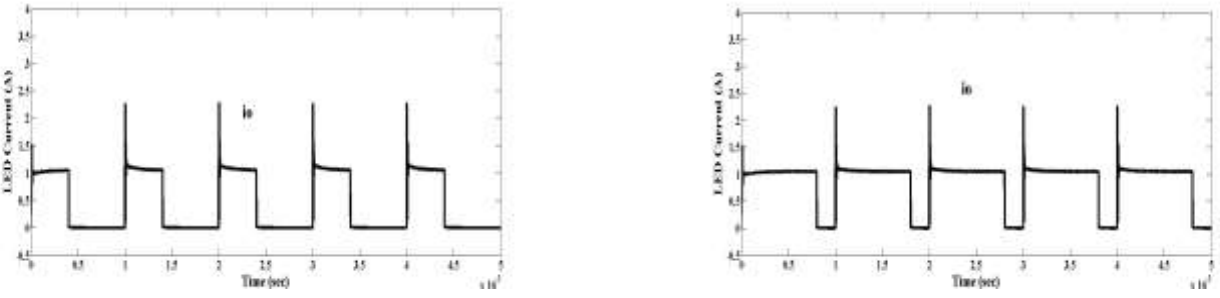


Fig. 10 Rectified Voltage V_0 and LED current i_0 under discharge condition (f_s=200 kHz)



a b

Fig. 11 LED current i_0 for various dimming levels

a. 40 % dimming b. 80 % dimming

required voltage is obtained at a frequency (f_s) of 200 kHz. The current in LED can be regulated by varying the switching frequency for any variations in supply voltage.

Fig. 5 shows simulation waveforms of line to line voltages of the 3-φ inverter (V_{ab}, V_{bc}, V_{ca}) when f_s = 210 kHz. Fig. 6 shows simulation waveforms of line to line capacitor voltages or the input to the 3-φ diode bridge rectifier (V_{AB}, V_{BC}, V_{CA}) when f_s = 210 kHz. Each leg is 120° phase shifted with respect to each other. Fig. 7 indicates rectified voltage V_0 and the LED current when f_s = 210 kHz .

Fig. 8 shows simulation waveforms of line to line voltages of the 3-φ inverter (V_{ab}, V_{bc}, V_{ca}) when f_s = 200 kHz. Fig. 9 shows simulation waveforms of line to line capacitor voltages or the input to the 3-φ diode bridge rectifier (V_{AB}, V_{BC}, V_{CA}) when f_s = 200 kHz. Each leg is 120° phase shifted with respect to each other. Fig. 10 indicates rectified voltage V_0 and the LED current when f_s = 200 kHz i.e., under battery discharge condition.

The frequency of the rectified voltage becomes six times of switching frequency f_s so that the voltage ripple comes down to a lower value. Hence the value of output inductor required for current ripple to be in specified limits will be small. To limit a current ripple to 3.5 %, inductor L_0 of 10 µH is sufficient, thereby eliminating any need of filter capacitor.

Fig. 11 a and b shows the LED current waveforms at 40 % and 60 % of dimming respectively.

VII. CONCLUSION

A 3-φ full-bridge parallel loaded resonant converter based LED driver for lighting application is proposed in this paper. By using 3-φ converter the output voltage has considerably reduced amount of ripple. Hence the proposed converter uses small inductor to minimize the ripple current in LED and thereby eliminates use of filter capacitor. This increases the life span of LED driver. Also cost and size of the driver are reduced proportionately. ZVS is achieved in the proposed converter using parallel loaded LC resonant circuit. Therefore switching losses are reduced increasing converter efficiency. The LED current is regulated by varying the switching frequency for any input voltage variations. Dimming is achieved in the proposed converter for varying the illumination of LED lighting. The power handling capacity of the proposed converter is high. Hence it can be used for larger power applications like street lighting, commercial lighting, industrial lighting, etc.

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