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ADC Controlled Half-Bridge LC Series Resonant Converter for LED Lighting

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***Abstract*— In this paper, a soft switched LED driver is proposed for LED lighting applications. It consists of half-bridge LC series resonant converter. The converter output is connected in series with DC voltage to drive the LED load. Asymmetric Duty Cycle control (ADC) is used. The proposed driver offers the features of dimming control, voltage regulation and current regulation in LED loads. It provides less ripple content and eliminates the need of bulk electrolytic capacitors. This configuration can be extended to multiple loads. The detailed description, circuit analysis and simulation results of the proposed converter are presented.**

Keywords—half-bridge series resonant converter; ZVS; PWM dimming; voltage regulation; ADC control; LED lighting.

I. INTRODUCTION

Nowadays, because of various advantages like high luminous efficiency, ease of drive, long lifetime, the use of high brightness light emitting diode (HB-LED) is increasing a lot, especially for outdoor lighting applications such as street lights. LEDs operate at low-voltage DC supply. LED brightness depends mainly on its current and it should be maintained constant irrespective of various illumination levels. Therefore, an efficient LED driver is required to control the LED current. LED drivers are generally enclosed in sealed case, limiting the mechanical dimensions. Thereby LED drivers having minimum size with less number of components, high efficiency along with simple dimming control are preferred. Different LED driver topologies have been proposed in the literature. Generally the driving circuit design affects the efficiency considerably. Hence it is necessary to design appropriate driving circuits for LEDs. Among various LED driver circuits, switching regulators are one of the popular and economical driving solutions.

There are LED drivers based on conventional DC-DC converters. In [1], two input buck converter has been proposed, with reduction in voltage stress across the switching devices along with efficiency improvement. LED driver based on interleaving technique is proposed in [2], where there is possibility of reduction in ripple current along with relatively lesser values of reactive components. Soft switching techniques can be employed in LED drivers so that the power conversion efficiency is still improved. In [3], zero current switching (ZCS) is employed in switched capacitor converter for LED driver applications. Resonant converters can also be used for LED driver applications [4]. In [5], [6], class-D resonant converter with zero voltage switching (ZVS) is used for LED driver application. Full-bridge DC-DC resonant topology based LED driver circuits are proposed for multiple LED string applications in [7], [8]. The most commonly used resonant converter is LC series resonant converter. LC Series Resonant Converter based LED driver using full-bridge inverter is proposed in [9] where a DC voltage source and resonant converter are cascaded in series. Here the cut in voltage is supplied by DC bus and current regulation is achieved by the full-bridge resonant converter. Here the number of components used is more and the output capacitance value is high. In order to regulate LED lighting levels according to human requirement and to achieve energy saving LED dimming control is employed. It is an important consideration for multiple LED lighting applications. There are different types of dimming techniques available in the literature. Among these the popular methods in switched-mode LED driver circuits are amplitude dimming and Pulse-Width Modulation (PWM) dimming. PWM dimming method is efficient as it varies the average LED current with the amplitude of the current maintained constant.

This paper proposes an LED driver using Half-bridge asymmetrical LC series resonant converter. The resonant converter acts as the current regulator and its output is connected in series with DC voltage source to drive the LED loads. It can be used for lighting applications like residential applications with dimming control. It uses Asymmetrical Duty Cycle (ADC) control in order to control the output of half bridge inverter and for regulating the forward current of LED. Dimming control can be employed in the proposed converter. Line voltage regulation is also possible using the proposed converter. It offers high efficiency due to reduced switching and conduction losses. 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. Simulation results are presented in section VI. Section VII states the conclusions of the proposed LED driver.

II. PRINCIPLE OF OPERATION

The proposed single-stage half bridge asymmetrical LC series resonant converter topology is shown in Fig.1 and its equivalent circuit is shown in Fig. 2. The half bridge

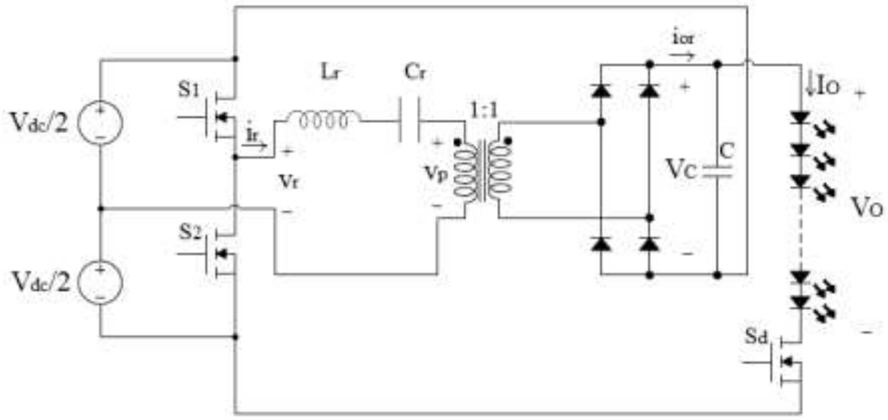


Fig. 1 Proposed Half bridge Asymmetrical Series Resonant Converter LED driver

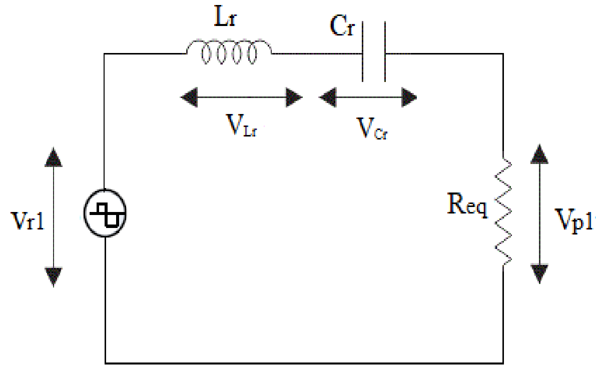


Fig. 2. Equivalent circuit of Series Resonant Converter

asymmetrical LC series resonant converter is connected in series with the DC voltage to drive the LED load. LED voltage is sum of the output voltage V_c and DC voltage, V_{dc}. Dimming switch S_d is connected in series with the LED load.

The half bridge resonant converter is operated at high switching frequency of 200 kHz. A square wave is generated from half bridge inverter which is applied to the series LC resonant tank. The switching frequency is selected to be slightly greater than the resonant frequency such that ZVS can be obtained. This will help in achieving minimum switching losses and thereby high efficiency. The current flowing in LC resonant circuit is nearly sinusoidal in nature. This sinusoidal ac current is fed to the full bridge diode rectifier through isolation transformer. A filter capacitor is used which removes the current ripple. This output voltage is added with DC source voltage. Hence a major portion of LED voltage is supplied by the DC voltage source. Only the small controllable power is fed through the asymmetrical LC series resonant converter. Hence the conversion losses are very small and thereby improving the overall converter efficiency. As only small power is controlled by the resonant converter many advantages can be seen as compared to the conventional converters. As the voltage required for controlling current is very less compared to cut in voltage, the voltage and current stresses are decreased significantly. As the output current of the resonant converter has less amount of ripple to be reduced by capacitor, the need of electrolytic capacitor is avoided making the life span of LED driver long and thereby increasing the reliability. As the losses are reduced significantly, this converter can easily be employed for higher power ratings as well. Dimming can also be achieved in this proposed converter by operating switch at low frequency i.e., 1 kHz. The forward current of LED is maintained constant through ADC control of half bridge inverter against source voltage variation.

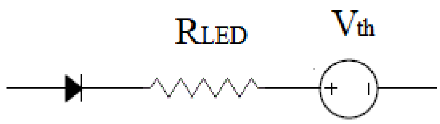


Fig. 3 *LED Equivalent Circuit*

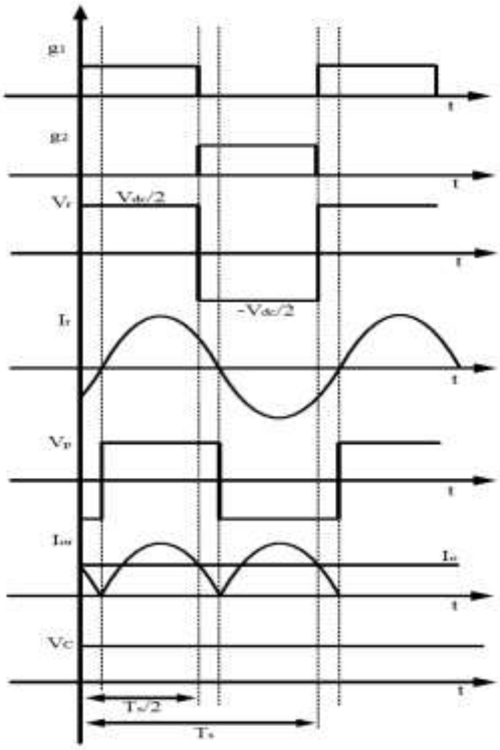


Fig. 4 Operating waveforms

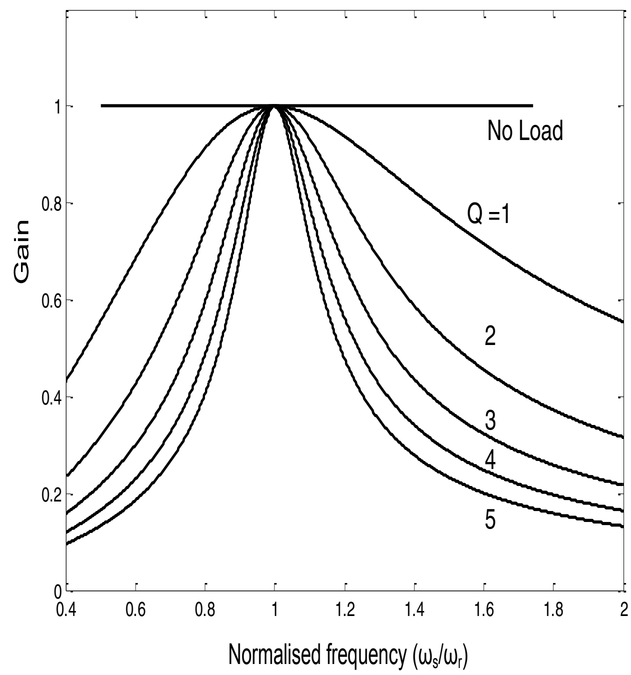


Fig. 5 Graph between normalized angular frequency and voltage gain V_0/V_{dc} for various values of Q

III. CIRCUIT ANALYSIS

The analysis of the proposed LED driver is carried out by considering the following assumptions.

- The proposed converter is operating in steady state
- The circuit components are ideal.

The LED load equivalent circuit is shown in Fig. 3. It comprises of a series combination of cut-in or threshold voltage Vth, internal resistance of LED, R_{LED} and an ideal diode. The voltage across the LED lamp can be defined as

$$V_0 = V_{th} + I_0 R_{LED} \tag{1}$$

The LED load is driven by a DC bus voltage and resonant converter in series as shown in Fig.1. The total voltage across the LED load can be expressed as

$$V_{dc} + V_c = V_0 \tag{2}$$

The square voltage obtained from half bridge inverter is applied across the series LC resonant tank circuit.

Fig. 4 shows the gate pulses of S1 and S2, half bridge inverter output voltage V_{r1}, the tank current i_s, transformer primary voltage v_p, rectified current waveform i_{or} and corresponding voltage waveform across capacitor V_c.

The AC equivalent circuit of LC resonant tank obtained by First Harmonic Analysis (FHA) method is shown in Fig. 2 where Vs is the fundamental voltage of input voltage for resonance network, R_{eq} is the equivalent load resistance.

The voltages Vs1, Vp1 and Req can be expressed as

$$V_{r1} = \frac{2V_{dc}}{\pi} \tag{3}$$

$$V_{p1} = \frac{4V_c}{\pi} \tag{4}$$

$$\mathrm{R}_{eq} = \frac{8}{\pi^2}\left(\frac{N_1}{N_2}\right)^2 R_{LED} \tag{5}$$

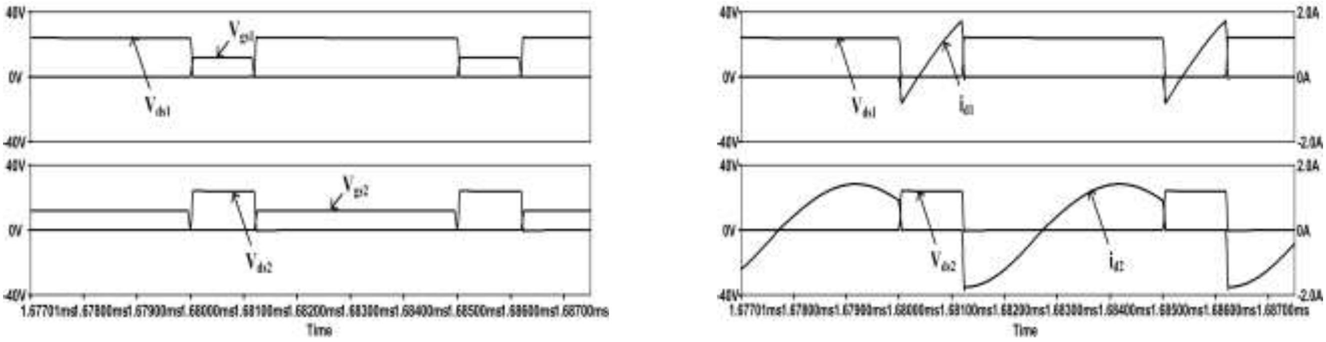
Where N_1 and N_2 are the turns ratio of isolation transformer (N_1/N_2=1:1).

The switching frequency f_s is greater than f_r making the current is lag with respect to voltage v_r. From Fig. 2*b*, the DC voltage conversion ratio equation of LC series-resonant converter in the ideal condition is obtained as below

$$\frac{V_{p1}}{V_{r1}} = \frac{1}{\sqrt{1+\left[\left(X_L - X_C\right)/\mathrm{Re}q\right]^2}} \tag{6}$$

where reactances X_L and X_C are

$$X_L = \omega_s L_r \tag{7}$$



a *b*

Fig. 6 Simulation waveforms at full illumination level indicating ZVS at nominal voltage
(a) Switch voltage and gate pulse of Switches S_1 and S_2,
(b) Voltage and current of Switches S_1 and S_2

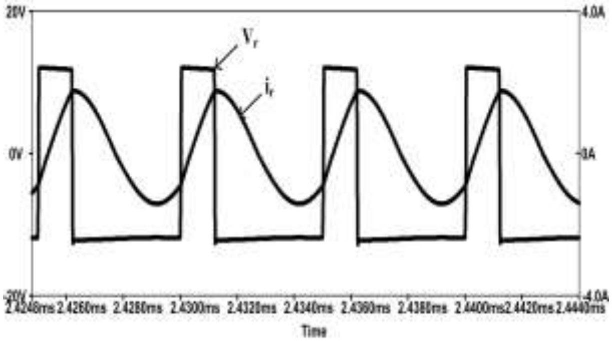


Fig. 7 Simulation waveforms of tank voltage and current at nominal voltage

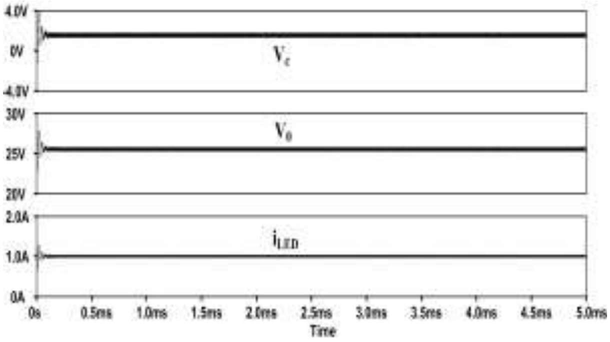


Fig. 8 Simulation waveforms of capacitor voltage, LED voltage and LED current at nominal voltage

$$X_c = \frac{1}{\omega_s C_r} \qquad (8)$$

$$\omega_s = 2\pi f_s \qquad (9)$$

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

The quality factor the LC series resonant converter is given as

$$Q = \frac{\omega_s L_r}{R_{eq}} = \frac{1}{\omega_s R_{eq} C_r} \qquad (10)$$

By substituting Eqns. (3), (4) in Eqn. (6), the relation between capacitor voltage and input voltage i.e, the resonant converter voltage gain can be written as

$$\frac{V_c}{V_{dc}} = \frac{1}{2}\frac{1}{\sqrt{1+\left[\left(X_L - X_C\right)/\mathrm{Re}q\right]^2}} \qquad (11)$$

By substituting Eqns. (7), (8), (10) in (11), we get

$$\frac{V_c}{V_{dc}} = \frac{1}{2}\frac{1}{\left[1+Q^2\left[\left(\omega_s/\omega_r\right)-\left(\omega_r/\omega_s\right)\right]^2\right]} \qquad (12)$$

Fig. 5 shows the graph plotted between gain V_o/V_{dc} and normalized angular frequency for various values of quality factor, Q.

Table 1 Parameters of proposed LED driver

DC voltage, V_{dc}	24 V
Output Voltage	25.5 V
Rated Power	28W
Number of parallel strings	2
Number of LEDs used in each parallel string	7
LED operating current, i_{LED}	550 mA
Switching frequency, f_s	200 kHz
Duty ratio of switches in bridge configuration	0.24
L_r	17.5 µH
C_r	50 nF
PWM dimming frequency	1 kHz
Duty ratio of dimming switches S_d	0 to 1
Resonant frequency, f_r	170.14 kHz

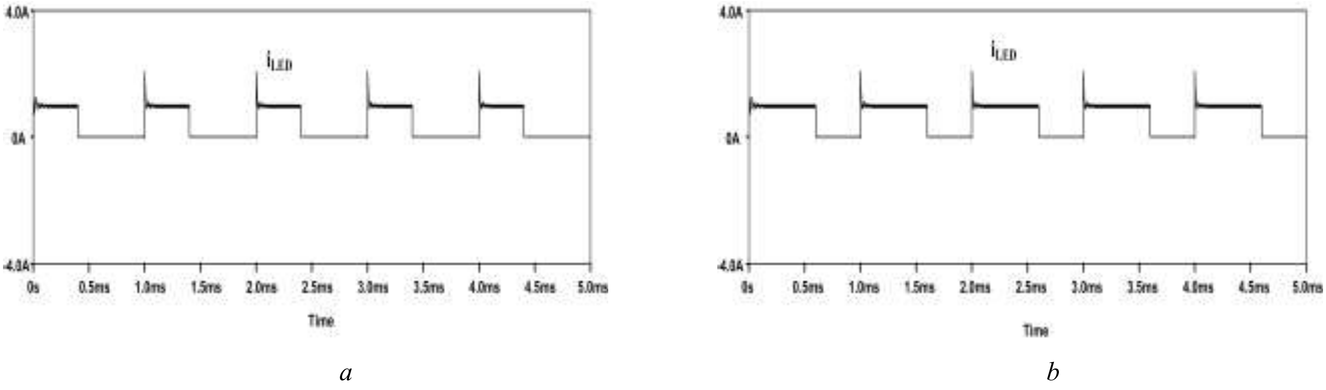


Fig. 9 Simulation waveforms of LED current indicating dimming control
(a) 40% dimming
(b) 60% dimming

IV. DESIGN CONSIDERATIONS

In the proposed work LED load comprises of two strings of LEDs which are connected in parallel. In each string, 7 LEDs are connected in series. Each LED is operated at 3.61 V, 550 mA and 1.9855 W. Thereby LED lamp is operated at 25.45 V, 1.1A and 28 W.

The switching frequency is chosen as 200 kHz. For f_s/f_r ratio of 1.17, resonant frequency (f_r) of the converter is calculated as

$$f_r = \frac{f_s}{1.17} = 170.143 \text{ kHz}$$

The relation between f_r, L_r and C_r is given by

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \qquad (13)$$

The value of capacitance (C_r) is taken as 50nF. 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. (13)

$$L_r = \frac{1}{(2\pi f_r)^2 C_r} \qquad (14)$$

L_r is calculated as 17.5µH.

From Eqn. 2, the LED voltage is given by

$$V_0 = V_{dc} + V_c$$

V_c can be adjusted by varying the duty ratio upto 50% to get the required output voltage.

The filter capacitor C is taken as 1.88 µF which is a small value and need not be an electrolytic capacitor.

V. DIMMING CONTROL

Dimming is required for adjusting the brightness of LED. Generally used dimming technique being 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. 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.

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 voltage V_{dc} is chosen as 24V.

Fig. 6*a* shows simulation waveforms of switch voltage and gating pulses of switches S_1 and S_2 respectively. Fig. 6*b* shows simulation waveforms of switch current and voltages of switches S_1 and S_2 respectively. Fig. 7 indicates simulation waveforms of tank voltage and tank current. Fig. 8 represents the capacitor voltage V_c for 24% duty ratio, LED voltage and lamp current waveforms under nominal voltage condition.

The required output voltage for a rated current of 1.1A is 25.5V. At nominal voltage of V_{dc} = 24V, the required voltage is obtained at a duty ratio of 24%. The output capacitor Co is chosen such that both voltage and current ripples are in their specified limits. A voltage ripple of around 1.89% and a ripple in current of 5.96% is observed.

Fig. 9*a* and *b* shows the lamp current waveforms at 40% and 60% of dimming control respectively.

The proposed converter can be operated from batteries. Consider the converter is operated from 12V batteries each. Let us consider a battery discharge of 10% i.e., a 1.2V reduction in both batteries. The input voltage becomes 10.8V each accounting to a voltage V_{dc} = 21.6V. The remaining 3.9V is supplied by the capacitor (V_c) by adjusting the duty ratio of half bridge series resonant converter. The required voltage is

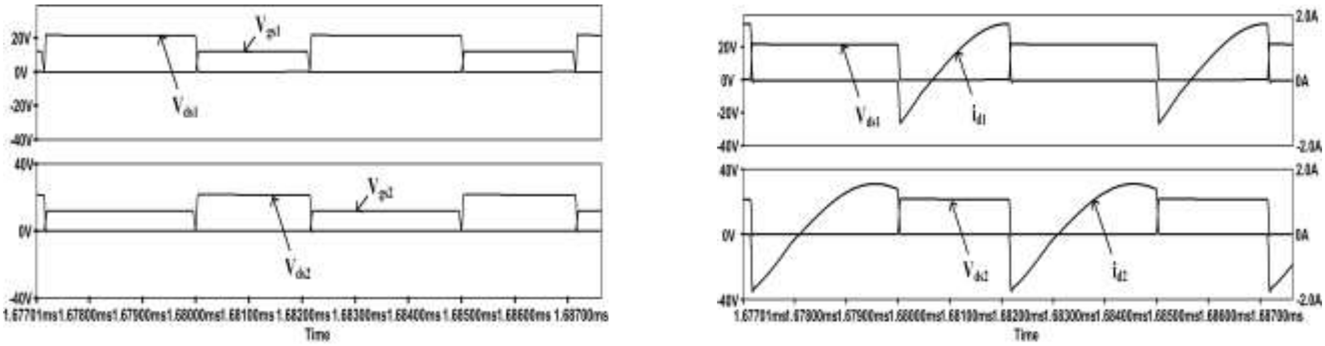


Fig. 10 Simulation waveforms at full illumination level indicating ZVS under discharge condition
(a) Switch voltage and gate pulse of Switches S_1 and S_2,
(b) Voltage and current of Switches S_1 and S_2

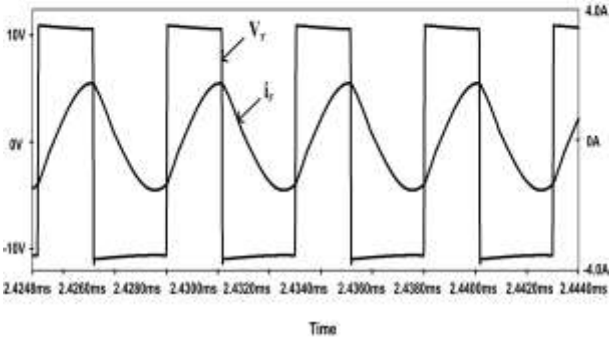


Fig. 11 Simulation waveforms of tank voltage and current under discharge condition

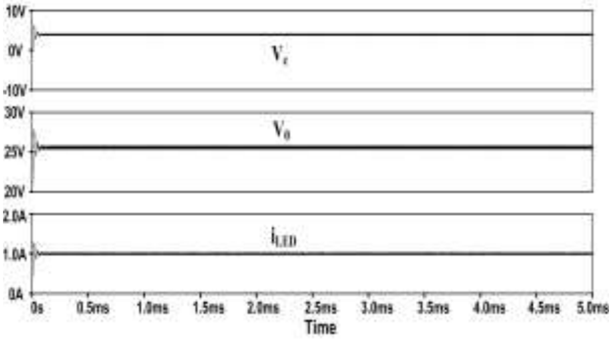


Fig. 12 Simulation waveforms of capacitor voltage, LED voltage and LED current under discharge condition

obtained at a duty ratio of 43%. The voltage ripple and current ripple under this condition is observed to be nearly same i.e., 1.41 % and 4.53 % respectively. Fig. 10*a* shows simulation waveforms of switch voltage and gating pulses of switches S_1 and S_2 respectively under discharge condition. Fig. 10*b* shows simulation waveforms of switch current and voltages of switches S_1 and S_2 respectively at 43% duty ratio. Fig. 11 indicates simulation waveforms of tank voltage and tank current under this condition. Fig. 12 represents the capacitor voltage V_c for 43% duty ratio, LED voltage and lamp current waveforms at adjusted duty ratio.

VII. CONCLUSION

An ADC controlled series resonant, electrolytic capacitor less LED driver has been proposed in this paper. The converter can be used for LED lighting applications. Most of the power is processed by dc voltage and the power required for current regulation is supplied by capacitor voltage. Since small amount of voltage is switched, voltage stresses on switches are reduced. As soft switching is employed, switching losses are less. There is no need of bulky electrolytic capacitor thereby increasing reliability. Dimming is incorporated in the proposed driver using a switch. There is a possibility of adding multiple loads.

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