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Soft switched LED Driver for multiple lighting system with independent control

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***Abstract*— In this paper, a half-bridge series resonant converter based LED driver is proposed. ADC method is employed for regulating LED current. Here two LED loads are driven using two half-bridge converters. ZVS is achieved in the proposed converter using series LC resonance. Therefore switching losses are reduced which increases the converter efficiency. Ripple current is reduced using filter inductor thereby eliminating electrolytic capacitor. Thus lifespan of LED driver increases. Dimming is achieved in the proposed converter. Proposed converter also regulates LED current against input voltage variations. The detailed description, circuit analysis and simulation results of the proposed converter are presented.**

Keywords—LED driver, ADC, ZVS operation, multiple loads

I. INTRODUCTION

Due to the global warming and depletion of natural resources, energy conservation is a challenge in these days. Energy consumption through lighting plays crucial role in overall energy conservation. Among various lighting sources, High brightness light emitting diode (HB-LED) is gaining importance these days due to its enormous advantages like high luminous efficacy, long life, high reliability, fast dynamic response, environmental friendly etc. AC or DC source can be used to drive LED load. For low power applications, DC from battery is sufficient to drive LED load. LED driver acts as an interface between LED load and source to apply the required load voltage and as current regulator for regulating LED current. Among various available DC-DC converters, switch mode power supplies are generally employed as LED drivers. But the classical converters like buck, boost, buck-boost converters have drawback of high voltage ripple which are minimized by using electrolytic capacitors. LEDs generally have life span of more than 100,000 hours [1]. But as these electrolytic capacitors have reduced life span of 10,000 hours [2], these in turn reduce the total life span of LED driver. Also the classical converters have high switching stress across the switches. Dimming is a method by which illumination is controlled with energy saving. LED drivers must be capable of providing dimming feature. Multiple LED loads also need to be driven sometimes where independent control is an important consideration. To overcome the above issues there is a requirement of advanced LED driver which can drive multiple loads with high efficiency, low switching stress, inbuilt dimming feature and which can eliminate electrolytic capacitor increasing life span of LED driver.

In [3], boost based LED driver is discussed with multiple LED loads controlled using multiphase pulse width modulation technique. An electrolytic capacitor used here reduces the life span of LED driver. Resonant converters can be used for LED drivers by using which zero voltage switching (ZVS) or zero current switching (ZCS) can be obtained. Zero current switching (ZCS) incorporated LED driver is discussed in [4]. In [5] class-D resonant converter with ZVS is employed for LED lighting application. Half bridge and full bridge converters can be employed for lighting applications. In [6], full bridge based resonant converters are used for LED driver applications. In [7], a 4 output DC-DC LED driver based on charge exchanging and balancing principle in the secondary resonant capacitors is discussed. In [8], non-resonant multichannel LED driver with soft switching is proposed. In [9], a single-switch coupled-inductor based two channel LED driver is proposed.

This paper proposes an LED driver based on half-bridge series LC resonance circuit. Series LC resonance is used for employing ZVS thereby reducing switching stress across the switches. The proposed topology uses two half bridge networks for driving two LED loads. This can be extended to multiple loads also. Independent load control is also possible with the proposed converter. Ripple content in LED current is reduced by using a filter inductor in series, which eliminates the use of electrolytic capacitors. Thus, increasing the life span of LED driver. Asymmetrical Duty Cycle (ADC) control is used in the proposed converter for regulating the LED current. Line regulation is possible under supply voltage variations. Dimming is also achieved in the proposed converter by employing low frequency switching. 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, simulation results are discussed. Finally Section VI states the conclusions of the proposed LED driver.

II. PRINCIPLE OF OPERATION

The proposed ADC controlled half bridge series LC resonance based LED driver is shown in Fig.1. The proposed circuit is driven by two equal sources, $E_{DC}/2$, with switches S_1, S_2, S_3 and S_4. L_{r1}, C_{r1}, L_{r2} and C_{r2} are the resonance inductors and capacitors. L_1 and L_2 are the filter inductors. S_1, S_2 are complementary switches and S_3, S_4 are complementary

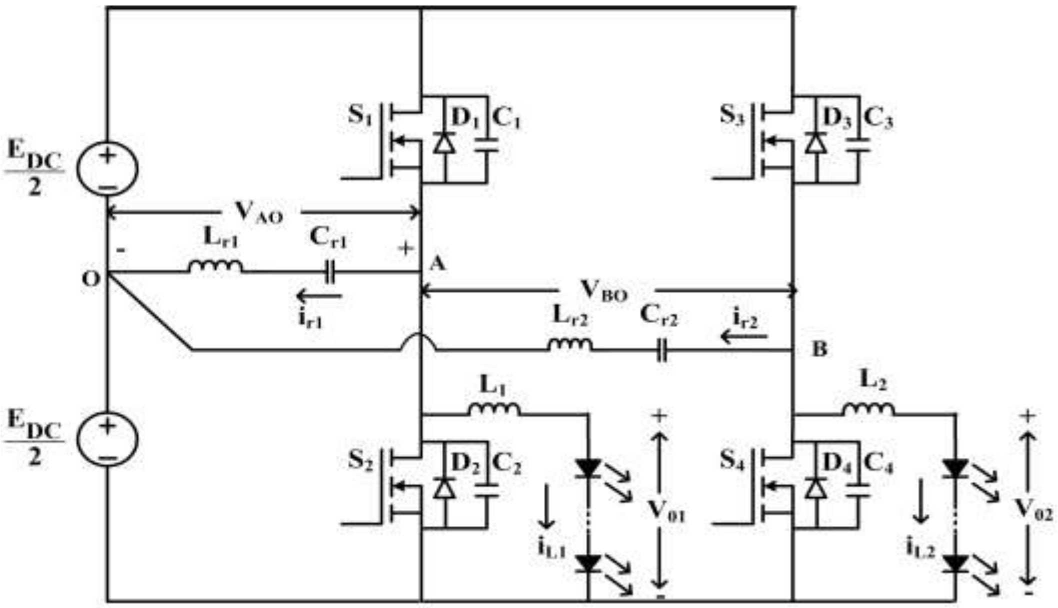


Fig. 1 Proposed LED driver

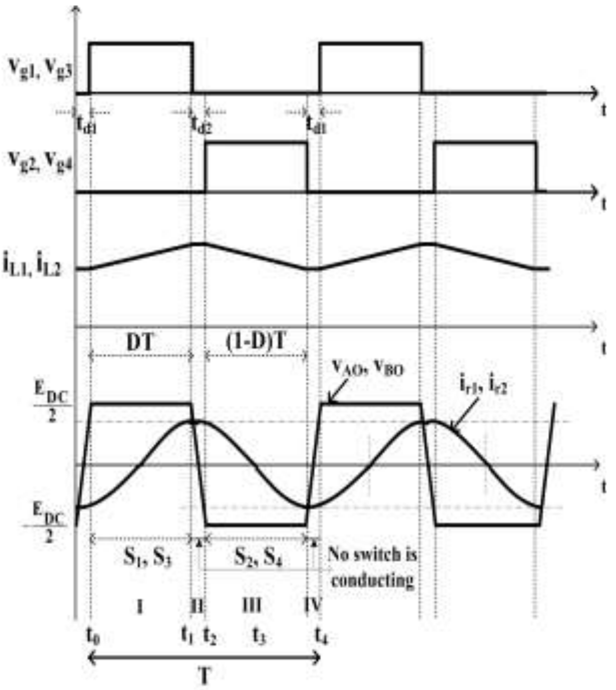


Fig. 2 Operating waveforms

switches. The proposed circuit drives two equal LED loads. Therefore the two half bridges are operated simultaneously i.e., with same duty cycles. Switches S_1, S_2 and S_3, S_4 are operated at 50 % duty cycle with switching frequency, f_s = 200 kHz. Fig.2 shows the operating waveforms of the proposed converter.

The various modes of operation for the proposed converter are discussed by considering first half-bridge series resonant circuit which drives LED Lamp-1. The same can be analyzed for second half-bridge series resonant circuit which drives LED Lamp-2. Fig. 3a and b represents the modes of operation when S_1 or S_3 is ON. Fig 4a and b represent the modes of operation when S_2 or S_4 is ON.

Modes of operation:

Mode-I:

Initially, switch S_1 only conducts. Positive voltage from top source is applied across resonance elements. Initial current in resonance inductor, i_{r1} in first half bridge freewheels through switch S_1 and top source. A voltage of E_{DC} ($E_{DC}/2$ + $E_{DC}/2$) is applied across LED Lamp-1. Load current, i_{L1} flows through both sources, S_1, L_1 and LED Lamp-1. i_{L1} increases linearly.

Mode-II:

Voltage across switch S_1 is zero. Now switch S_1 is turned OFF. The inductor current i_{r1} is considered to be constant in this duration. Capacitor C_1 and capacitor C_2 charges and discharges respectively. When C_2 charges to forward voltage of diode D_2, D_2 starts conducting. Now voltage across S_2 is zero. At this point switch S_2 is given gate pulse and turned ON. Thus, switch S_1 is turned OFF and switch S_2 is turned ON at zero voltage i.e., ZVS is achieved by series LC resonance.

Mode-III:

Now Switch S_2 only conducts. A negative voltage from bottom source is applied across resonance elements. Resonance inductor current, i_{r1} in first half-bridge freewheels through LED Lamp-1 and switch S_2. i_{L1} decreases linearly through L_1→Lamp-1→S_2.

Mode-IV:

Voltage across switch S_2 is zero. Now switch S_2 is turned OFF. The inductor current i_{r1} is considered to be constant at the earlier value in this duration. Capacitor C_1 and capacitor C_2

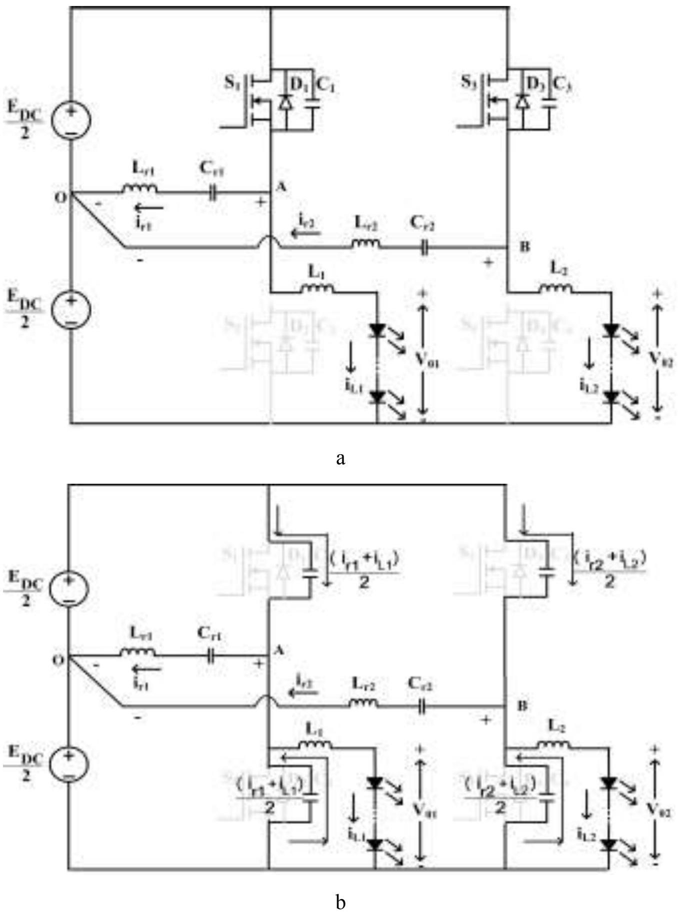


Fig. 3 Modes of Operation

a. Mode I b. Mode II

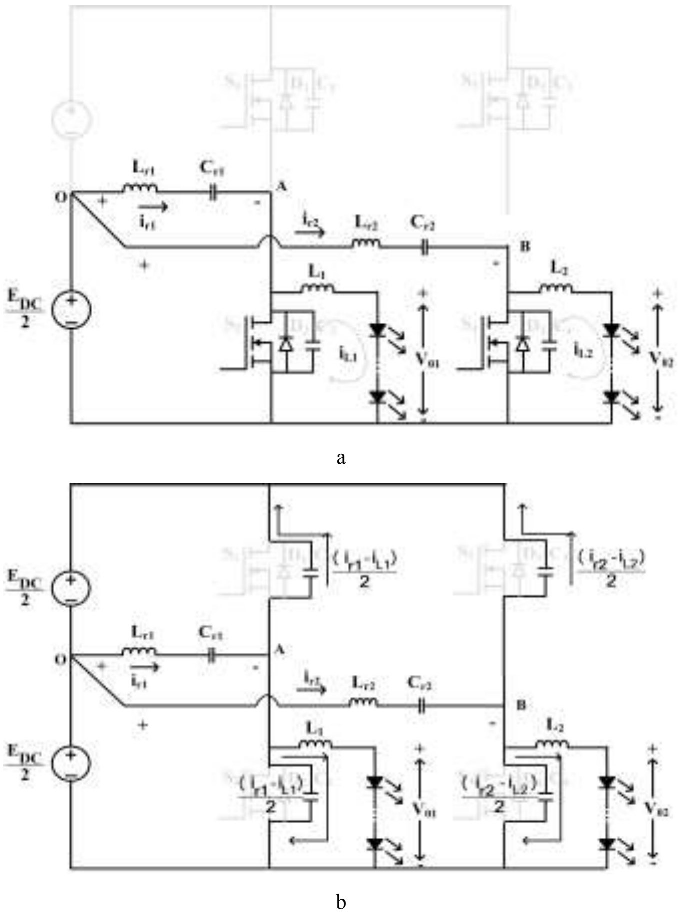


Fig. 4 Modes of Operation

a. Mode III b. Mode IV

discharges and charges respectively. When C_1 charges to forward voltage of diode D_1, D_1 starts conducting. Now voltage across S_1 is zero. At this point switch S_1 is given gate pulse and turned ON. Thus, switch S_1 is turned ON and switch S_2 is turned OFF at zero voltage i.e., ZVS is achieved by series LC resonance.

The above modes are repeated for every cycle. The same operation applies for second half-bridge resonant circuit which drives LED Lamp-2.

The average current flowing through LED loads is the required load current. A square wave voltage with magnitude $E_{DC}/2$ is applied across series resonant elements. The current flowing in resonant inductors is sinusoidal in nature. ZVS is achieved across the switches using LC series resonance. Ripple in the LED current is reduced by using filter inductors L_1 and L_2. Therefore capacitors are eliminated in the proposed converter increasing the life span of LED driver. ADC control is used in the proposed converter for regulating LED current. Dimming is achieved in the proposed converter by interfacing the switching frequency with a low dimming frequency of 100 Hz. In a similar way multiple loads can be driven by the proposed converter.

Table 1 Parameters of proposed LED driver	
DC voltage, E_{DC}	60 V
Output Voltage	30 V
Rated Power	36 W
Number of parallel strings	2
Number of LEDs used in each parallel string	10
LED operating current, i_{LED}	600 mA
Switching frequency, f_s	200 kHz
Duty ratio of switches in bridge configuration	0.50
L_r	76.47 µH
C_r	10 nF
L_1, L_2	834 µH
Resonant frequency, f_r	182 kHz

III. CIRCUIT ANALYSIS

The analysis of the proposed LED driver is done by considering one half bridge series LC resonant converter and the same analysis can be carried to second half 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

(t_0-t_1):

The voltage across inductor L_1 is

$$v_{L1} = E_{DC} - V_{01} = L_1 \frac{di_{L1}}{dt} \qquad t_0 \le t < t_1 \qquad (1)$$

The current through the inductor L_1 is given by

$$i_{L1}(t) = \frac{1}{L_1}\int_{t_0}^{t} v_{L1}(t)\,dt + i_{L1}(t_0) \qquad t_0 \le t < t_1 \qquad (2)$$
$$= \frac{E_{DC} - V_{01}}{L_1}(t - t_0) + i_{L1}(t_0)$$

where $i_{L1}(t_0)$ is initial current in the inductor L_1 at time $t = t_0$. At $t = t_1$, $i_{L1}(t)$ reaches maximum value, which is

$$i_{L1}(t_1) = \frac{E_{DC} - V_{01}}{L_1}(t_1 - t_0) + i_{L1}(t_0) \qquad (3)$$

The duration $(t_1 - t_0)$ is the ON period of switches S_1. Hence Eqn. (3) can be written as

$$i_{L1}(t_1) = \frac{E_{DC} - V_{01}}{L_1} DT + i_{L1}(t_0) \qquad (4)$$

where D is duty ratio of switch S_1 and T is the switching period.
From Eqn. (4), the ripple current in inductor L_1 is expressed as

$$\Delta i_{L1} = i_{L1}(t_1) - i_{L1}(t_0) = \frac{E_{DC} - V_{01}}{L_1} DT \qquad (5)$$

In this interval, voltage across resonant circuit components L_r and C_r (V_{AO}) is $\frac{E_{DC}}{2}$. The current through it is expressed as

$$i_{r1}(t) = \frac{V_{AO}}{Z_0}\sin\omega_0(t - t_0) + i_{r1}(t_0)$$
$$= \frac{E_{DC}}{2}\sqrt{\frac{C_r}{L_r}}\sin\omega_0(t - t_0) + i_{r1}(t_0) \quad t_0 \le t < t_1 \qquad (6)$$

where Z_0 = Characteristic Impedance

$$= \sqrt{\frac{L_r}{C_r}};$$

$$\omega_0 = \frac{1}{\sqrt{L_r C_r}}$$

(t_2–t_3):

The voltage across inductor L_1 is

$$v_{L1} = -V_{01} = L_1 \frac{di_{L1}}{dt} \qquad t_2 \le t < t_3 \qquad (7)$$

The current through the inductor L_1 is expressed as

$$i_{L1}(t) = \frac{1}{L_1}\int_{t_2}^{t} v_{L1}(t)\,dt + i_{L1}(t_2) \qquad t_2 \le t < t_3 \qquad (8)$$
$$= \frac{V_{DC2} - V_{01}}{L_1}(t - t_2) + i_{L1}(t_2)$$

where $i_{L1}(t_2)$ is the initial current in inductor L_1 at time $t = t_2$. At $t = t_3$, $i_{L1}(t)$ reaches minimum value and is given by

$$i_{L1}(t_3) = \frac{V_{DC2} - V_{01}}{L_1}(t_3 - t_2) + i_{L1}(t_2) \qquad (9)$$

Assuming the dead times t_{d1} and t_{d2} to be negligible, the duration $(t_3 - t_2)$ is the OFF period of switches S_1. Eqn. (9) can be written as

$$i_{L1}(t_3) = \frac{E_{DC} - V_{01}}{L_1}(1 - D)T + i_{L1}(t_2) \qquad (10)$$

From Eqn. (10), the ripple current in inductor L_1 is expressed as

$$\Delta i_{L1} = i_{L1}(t_3) - i_{L1}(t_2) = \frac{E_{DC} - V_{01}}{L_1}(1 - D)T \qquad (11)$$

During this interval, voltage across resonant circuit components L_r and C_r (V_{AO}) is $-\frac{E_{DC}}{2}$.

$$i_{r1}(t) = \frac{V_{AO}}{Z_0}\sin\omega_0(t - t_2) + i_r(t_2)$$
$$= -\frac{E_{DC}}{2}\sqrt{\frac{C_r}{L_r}}\sin\omega_0(t - t_2) + i_{r1}(t_2) \quad t_2 \le t < t_3 \qquad (12)$$

Under steady state operation, the net value of current through inductor L_1 is zero during one switching cycle i.e., T. Hence from Eqns. (5) and (11)

$$[i_{L1}(t_1) - i_{L1}(t_0)] + [i_{L1}(t_3) - i_{L1}(t_2)] = 0 \qquad (13)$$

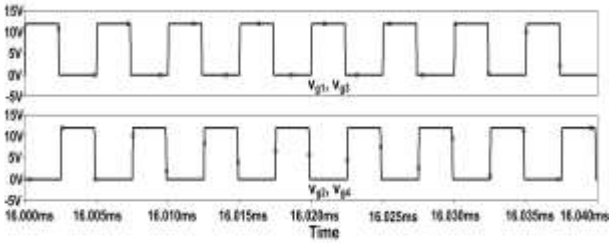
$$\Rightarrow \quad \frac{E_{DC} - V_{01}}{L_1} DT + \frac{E_{DC} - V_{01}}{L_1}(1 - D)T = 0 \qquad (14)$$

$$\Rightarrow \quad V_{01} = E_{DC} D \qquad (15)$$

The above analysis is also applicable for other load LED lamp-2. Eqns. (5), (11) and (15) are applicable to other LED lamps also. Hence, the ripple current through each LED lamp and voltage across each LED lamp are given by

$$\Delta i_{Lk} = \frac{E_{DC} - V_{0k}}{L_k} DT, \text{ where } k = 1, 2 \qquad (16)$$
$$= \frac{E_{DC} - V_{0k}}{L_k}(1 - D)T$$

$$V_{0k} = DE_{DC}, \text{ where } k = 1, 2 \qquad (17)$$



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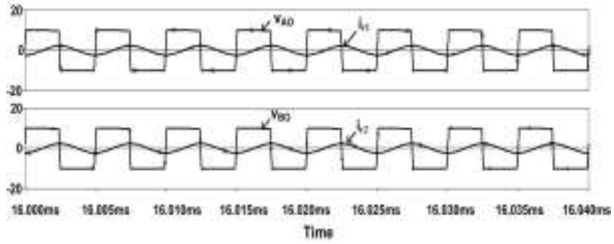

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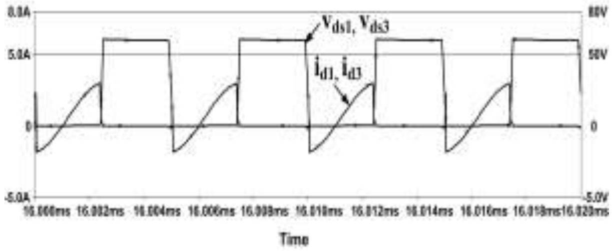
Fig. 5 a. Gate pulses of Switch S_1 or S_3 under nominal condition

b. Inverter output voltages (V_{AO}, V_{BO}) and inductor currents (i_{r1}, i_{r2}) of leg 1 and leg 2 under nominal condition



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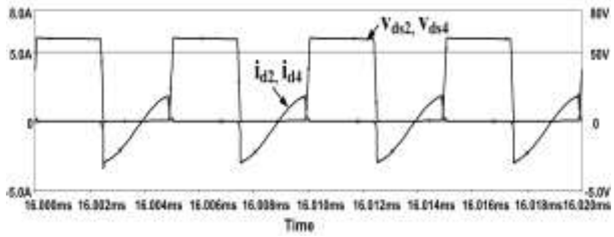

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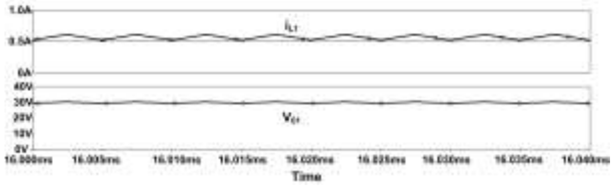
Fig. 6 a. Voltage across Switch and current through S_1 or S_3 under nominal condition

b. Voltage across Switch and current through S_2 or S_4 under nominal condition



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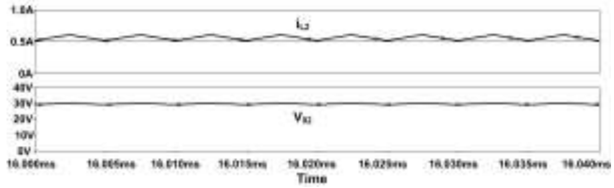

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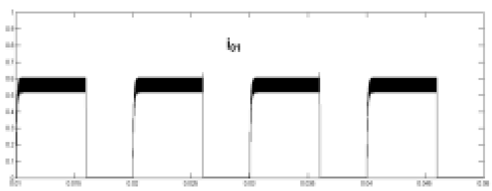
Fig. 7 a. Current through and voltage across LED Lamp-1 under nominal condition

b. Current through and voltage across LED Lamp-2 under nominal condition



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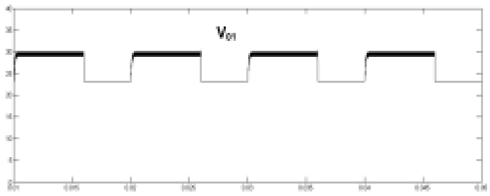

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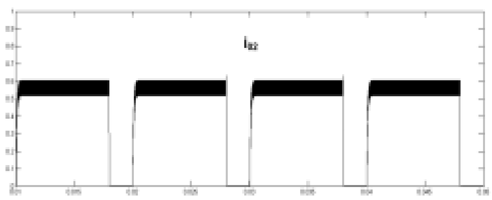

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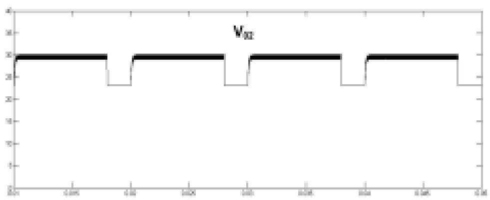
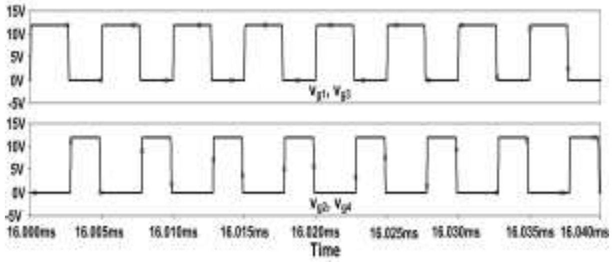


d

Fig. 8 a. Current through LED Lamp-1 at 60 % dimming b. Voltage across LED Lamp-1 at 60 % dimming

c. Current through LED Lamp-2 at 80 % dimming d. Voltage across LED Lamp-2 at 80 % dimming



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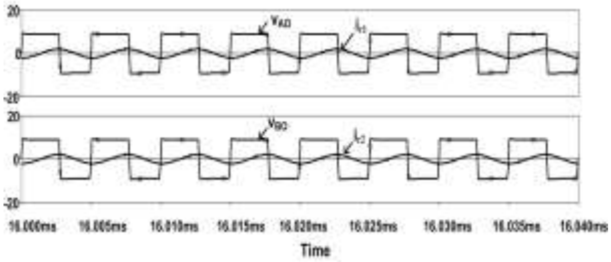
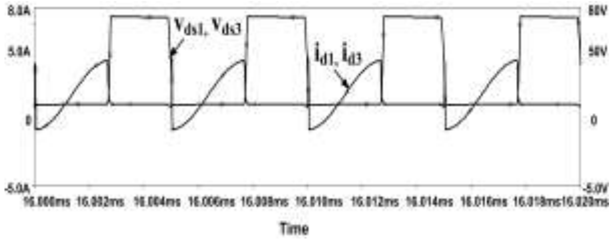


b

Fig. 9 a. Gate pulses of Switch S_1 or S_3 at 10 % input voltage variations (57 % duty ratio)

b. Inverter output voltages (V_{AO}, V_{BO}) and inductor currents (i_{r1}, i_{r2}) of leg 1 and leg 2 at 10 % input voltage variations (57 % duty ratio)



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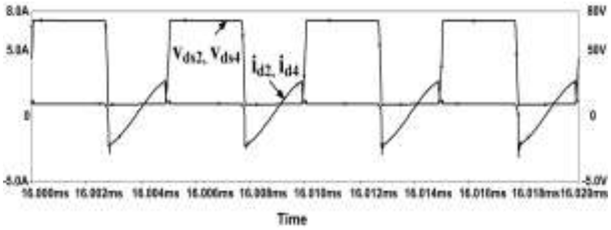

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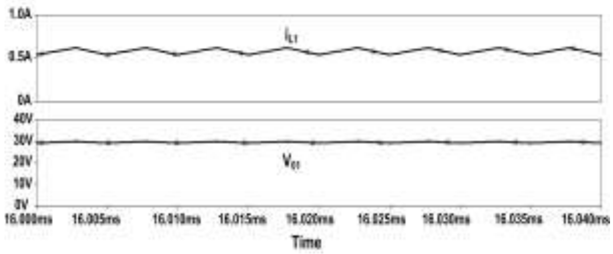
Fig. 10 a. Voltage across Switch and current through S_1 or S_3 under nominal condition at 10 % input voltage variations (57 % duty ratio)

b. Voltage across Switch and current through S_2 or S_4 under nominal condition at 10 % input voltage variations (57 % duty ratio)



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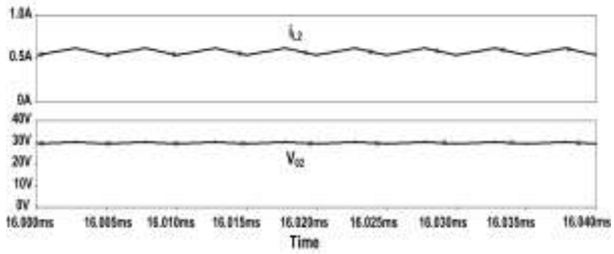

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Fig. 11 a. Current through and voltage across LED Lamp-1 at 10 % input voltage variations (57 % duty ratio)

b. Current through and voltage across LED Lamp-2 at 10 % input voltage variations (57 % duty ratio)

IV. DESIGN PROCEDURE

In the proposed circuit two LED lamps are used. In each case two parallel strings each consisting of 10 LEDs in series are used in order to test the performance of the proposed LED driver. The threshold voltage of each LED is 2.32 V. Each LED is operated at 3 V, 300 mA and 0.9 W.

So, each LED lamp is operated at 30 V, 600 mA and 18 W.

From Eqn. (17), input voltage is given by

$$E_{DC} = \frac{V_{0k}}{D}$$

Considering a duty ratio of 0.5, V_{0k} of 30 V, input voltage is calculated as

$$V_{in} = E_{DC} = 60V$$

Converter is operated at a high switching frequency of 200 kHz. Rearranging Eqn. (16)

$$L_1 = L_2 = \frac{E_{DC} - V_{0k}}{\Delta i_{Lk}} DT \quad (18)$$

For 200 kHz of switching frequency; E_{DC} = 60 V, V_{0k} = 30V, D = 0.5, T = 5 µs, limiting peak to peak LED current ripple Δi_{Lk} to 15%, the value of inductors from above equation is

$$L_1 = L_2 = 834\mu H$$

The resonant frequency (f_r) of the converter is determined by the resonant circuit components i.e., L_r and C_r as

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (19)$$

The resonant frequency f_r is chosen as 182 kHz. The value of capacitance (C_r) is taken as 10 nF. Certain 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 required current during dead time.

Rearranging Eqn. (22)

$$L_r = \frac{1}{(2\pi f_r)^2 C_r} \quad (20)$$

L_r is calculated as 76.47 μH.

V. SIMULATION RESULTS

The circuit parameters of the converter are listed in Table 1. The proposed LED driver has been first simulated in ORCAD PSpice software. The input voltage to the converter E_{DC} is chosen as 60 V. The duty ratio of switches S_1 and S_2 can be adjusted correspondingly for Lamp-1 if at all any variations in input voltage. Similarly, duty ratio of S_3 and S_4 is adjusted for Lamp-2 for input voltage variations.

Fig. 5 to Fig. 7 indicates the corresponding waveforms under nominal voltage conditions at 50 % duty ratio. Fig. 5*a* shows simulation waveforms of gating pulses of switches S_1 or S_3 and S_2 or S_4 respectively. Fig. 5b shows inverter output voltages (V_{AO}, V_{BO}) and inductor currents (i_{r1}, i_{r2}) of individual legs. Fig. 6a and b shows simulation waveforms of switch current and voltages of switches S_1 or S_3 and S_2, S_4 respectively. Fig. 6 shows that zero voltage switching is achieved at nominal voltage condition. Fig. 7a and b indicate simulation results of output voltage, LED current of Lamp-1 (V_{01}, i_{01}) and Lamp-2 (V_{02}, i_{02}) at nominal conditions.

Dimming can be achieved in proposed circuit by ANDing corresponding high frequency signal (200 kHz) with a low frequency (100 Hz) signal and applying to switches S_1 and S_2 for leg 1. Same explanation applies for leg 2. Fig. 8a and b represents the current in LED and voltage across LED of Lamp-1 at 60 % dimming respectively. Fig. 8c and d represents the current in LED and voltage across LED of Lamp-2 at 80 % dimming respectively. Thus it indicates independent control of dimming of the lamps. This can be extended to multiple loads and each lamp can be controlled independently.

Fig. 9 to Fig. 11 shows the corresponding waveforms considering input voltage variations of 10 % i.e., when E_{DC}=54 V. The required output voltage is obtained at a duty ratio of 57 %. Fig. 9a shows simulation waveforms of gating pulses of switches S_1, S_3 and S_2, S_4 respectively. Fig. 9b shows inverter output voltages (V_{AO}, V_{BO}) and inductor currents (i_{r1}, i_{r2}) of individual legs at 57 % duty ratio. Fig. 10a and b shows simulation waveforms of switch current and voltages of switches S_1 or S_3 and S_2, S_4 respectively. Fig. 11a and b indicates simulation results of output voltage, LED current of Lamp-1 (V_{01}, i_{01}) and Lamp-2 (V_{02}, i_{02}) for input voltage variation of 10 % at duty ratio of 57%.

VI. CONCLUSION

ADC controlled half-bridge series resonant based LED driver for LED lighting is proposed in this paper. LED current is regulated by using ADC control. ZVS is achieved in the proposed converter using series LC resonance. Therefore switching losses are reduced and thus efficiency is improved. LED ripple current is reduced by using a filter inductor which eliminates electrolytic capacitor. This improves the lifespan of LED driver. Dimming is also possible by the proposed converter. Two LED loads are driven by using two half-bridge series resonant converters in the proposed converter. In a similar way multiple loads can be driven by the proposed converter. Independent Control of every load is possible using the proposed converter.

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