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An Efficient Full-Bridge DC-DC Converter with Zero-Voltage Switching for LED Lighting Applications

Ch Kasi Ramakrishna Reddy
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

Abstract-In this paper, a soft switched LED driver is proposed for street light applications. It is suitable for high power lighting, as this driver uses a full bridge topology. It operates with ZVS and provides high efficiency. It offers the features of dimming control and constant peak current regulation in LED loads. This configuration is suitable for Solar PV fed LED lighting application. The detailed description and analysis of the circuit operation and simulation results are presented.

Key Words: Driver circuits, DC-DC Power converters, Light emitting diodes

I. INTRODUCTION

LED lighting possess a number of advantages like long life time, low power consumption, smaller size and faster response, compared to the conventional lighting methods. As the LEDs are current controlled devices, they require a driver circuit which provides constant current to LEDs.

LEDs can be easily driven compared to traditional sources. LED drivers are generally enclosed in sealed case, limiting the mechanical dimensions. Thereby LED drivers having minimum size with limited components, high efficiency along with simple dimming control are preferred. Different converter topologies have been proposed in the literature. Traditionally, the LED driver circuit uses basic switching regulators like buck, boost, buck-boost or fly-back converter [1-2]. In such a circuit structure, the converters have to process large power which are inefficient when the dimming function is performed [3]. In [4] LED driver based on two-input buck converter was proposed, with reduction in voltage stress across the switching devices along with efficiency improvement. In [5] LED driver based on interleaved scheme is proposed where there is possibility of reduction in ripple current along with relatively lesser values of reactive components. Soft switching techniques can also be implemented in LED drivers in order improve the power conversion efficiency. In [6] zero current switching (ZCS) is employed in switched capacitor converter for LED driver applications. Even resonant converters can be used for LED driver applications [7]. A class-D resonant converter with zero voltage switching (ZVS) is proposed for LED driver application [8, 9]. Based on full-bridge DC-DC resonant topology also LED driver circuits are proposed for multiple LED string applications [10, 11]. In [12] a resonant based buck converter with reduced cost and power are proposed for LED applications.

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 two popular methods for dimming LEDs in switched-mode driver circuits are Pulse-Width Modulation (PWM) dimming and analog dimming.

This paper proposes an LED driver circuit using full-bridge configuration which combines features like a) reduced current stress b) ZVS operation of switching devices c) reduced switch conduction loss d) high efficiency e) dimming control f) regulation of LED lamp current g) high power. Any filter capacitor and rectifier stage do not required. Operating principle of the proposed circuit is presented in section II. Analysis of operation of proposed LED driver is given in section III. In section IV, design procedure is explained. Dimming and regulation features are described in section V. Simulation are discussed in section VI. Section VII states the conclusions of the proposed work.

II. OPERATING PRINCIPLE OF PROPOSED LED DRIVER

The proposed LED driver circuit configuration is shown in Fig. 1. It utilizes a full-bridge configuration consisting of four power MOSFETs S_1, S_2, S_3, and S_4. D_1 – D_4 are the intrinsic body diodes of power MOSFETs and C_1 – C_4 indicate either the output capacitances of power MOSFETs or external capacitors. Each switch has a series connection of LED lamp and an inductor is in parallel. In proposed circuit, four LED lamps are present. The inductors L_1, L_2, L_3 and L_4 provide continuous current through lamp-1, lamp-2, lamp-3, and lamp-4 respectively. The inductor L_r is used to achieve zero voltage switching (ZVS) in bridge switches. The switches in each leg of full-bridge are alternately switched on and off at a frequency $f_s = 1/T$ with 50% duty ratio. A dead time is introduced between switching pulses of each leg. And during dead time the lamp currents and inductor current i_{Lr} are considered to be constant. A switch S_d is connected in series with input which incorporates dimming feature. Input voltage V_{in} is obtained from two dc voltages V_{DC1}

and V_B. V_{DC2} is input voltage to the source converter and V_B is its output voltage. To minimize the power processed by source converter, V_{DC1} must be far greater than V_{DC2}. The dc voltage sources V_{DC1} and V_{DC2} can be supplied from PV or battery operated system. For any variations in supply voltage, input voltage V_{in} is controlled to be constant by the source converter. The equivalent circuits in different working modes in a switching cycle are shown in Figs. 2, where the input voltage V_{in} is represented by a voltage source. Fig. 3 shows the operating waveforms of the proposed LED driver. The working modes are explained in this section.

Mode I: (t_0-t_1)

At time instant t_0, switches S_1 and S_4 are switched on at zero voltage. LED lamp-2 and lamp-3 are supplied by input voltage V_{in} and their currents increase linearly. LED lamp-1 and lamp-4 are supplied by stored energy in inductors L_1 and L_4 respectively and their currents decrease linearly. Due to positive voltage across inductor L_r, the current i_{Lr} linearly increases through the switches S_1 and S_4.

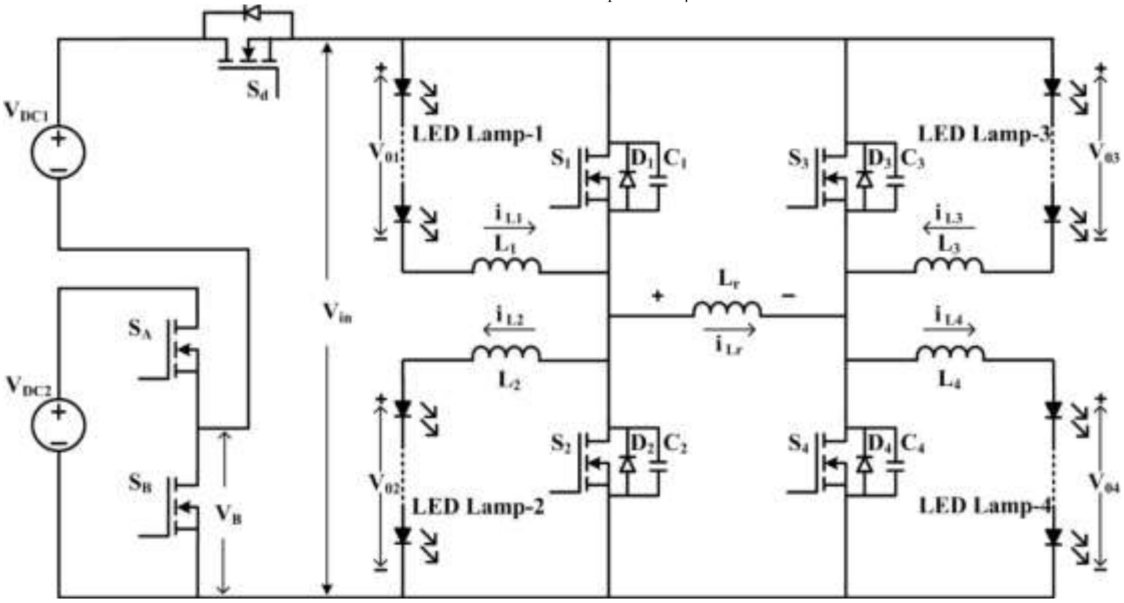


Fig.1 Proposed LED driver circuit configuration

S_1 conducts difference of i_{L2} and i_{L1} and S_4 conducts difference of i_{L3} and i_{L4}. Hence switches are carrying only a small value of current. Hence both device current stress and conduction losses are reduced. This mode ends at t_1.

Mode II: (t_1-t_2)

This mode starts after removing gate signals for switches S_1 and S_4, which are carrying positive currents. Switches S_1 and S_4 are switched off at zero voltage. During t_2 to t_3 none of the switches is conducting. In first leg, capacitor C_1 is charged and capacitor C_2 is discharged by current $(i_{Lr} + i_{L2} - i_{L1})/2$. Similarly, in second leg, capacitor C_4 is charged and capacitor C_3 is discharged by current $(i_{Lr} + i_{L3} - i_{L4})/2$. After this, D_2 and D_3 start conducting. Now the gate voltage for switches S_2 and S_3 may be given at zero voltage switching. This mode ends when capacitors C_2 and C_3 are discharged from V_{in} to zero or C_1 and C_4 are charged from zero to V_{in}.

Mode III: (t_2-t_3)

At time instant t_2, switches S_2 and S_3 are switched on at zero voltage. LED lamp-1 and lamp-4 are supplied by input voltage V_{in} and their currents increase linearly.. LED lamp-2 and lamp-3 are supplied by stored energy in inductors L_1 and L_4 respectively and their currents decrease linearly. Due to negative voltage across inductor L_r, the current i_{Lr} linearly decreases through the switches S_2 and S_3. S_2 conducts difference of i_{L1} and i_{L2} and S_3 conducts difference of i_{L4} and i_{L3}. As the switches carry a small current, device current stress and conduction losses are reduced. This mode ends at t_4.

Mode VI: (t_3-t_4)

This mode starts after removing gate signals for switches S_2 and S_3, which are carrying positive currents. The process of switching off of switches S_2, S_3 and switching on of switches S_1, S_4 with zero voltage is identical to that in mode II. This mode ends when capacitors C_1 and C_4 are discharged from V_{in} to zero or C_2 and C_3 are charged from zero to V_{in}.

III. ANALYSIS OF THE PROPOSED LED DRIVER

The following assumptions are considered to analyze the proposed driver.

i. The proposed converter is operating in steady state
ii. The circuit components are ideal
iii. All four LED lamps are identical
iv. The voltage across each LED lamp is constant

Fixed duty cycle control has been adopted in this driver. That means each switch is on for 50% duty cycle and off for remaining period. The voltage across each LED lamp is calculated by inductor current and voltage equations. The analysis is given for a single LED lamp, i.e LED lamp-2 due to identical nature of LED lamps. In mode-I, the LED lamp-2 is powered by input dc voltage V_{in} through the inductor L_2. The corresponding equivalent circuit is shown in Fig. 2(a).

The voltage across inductor L_2 is expressed as

$$v_{L2} = V_{in} - V_{02} = L_2 \frac{di_{L2}}{dt} \qquad t_0 \le t < t_1 \qquad (1)$$

The current through the inductor L_2 is

$$i_{L2}(t) = \frac{1}{L_2}\int_{t_0}^{t} v_{L2}(t)\,dt + i_{L2}(t_0) = \frac{V_{in} - V_{02}}{L_2}(t - t_0) + i_{L2}(t_0) \qquad t_0 \le t < t_1 \qquad (2)$$

where $i_{L2}(t_0)$ is the initial current in the inductor L_2 at time $t = t_0$.

The ripple current in inductor L_2 is expressed as

$$\Delta i_{L2} = i_{L2}(t_1) - i_{L2}(t_0) = \frac{V_{in} - V_{02}}{L_2} DT \qquad (3)$$

During this interval, voltage across L_r is V_{in}. The current through it increases linearly and is expressed as

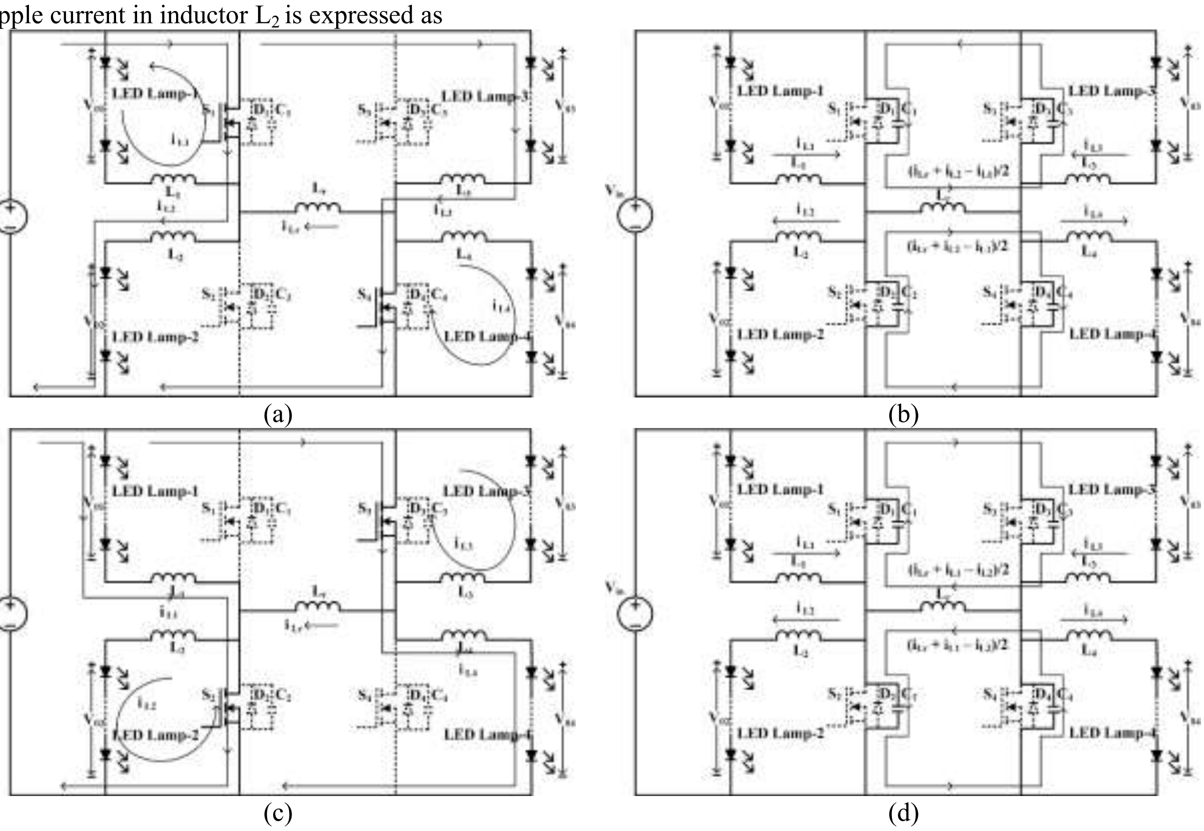


Fig. 2. Equivalent circuits of proposed LED driver. (a) Mode-I. (b) Mode-II. (c) Mode-III. (d) Mode-IV.

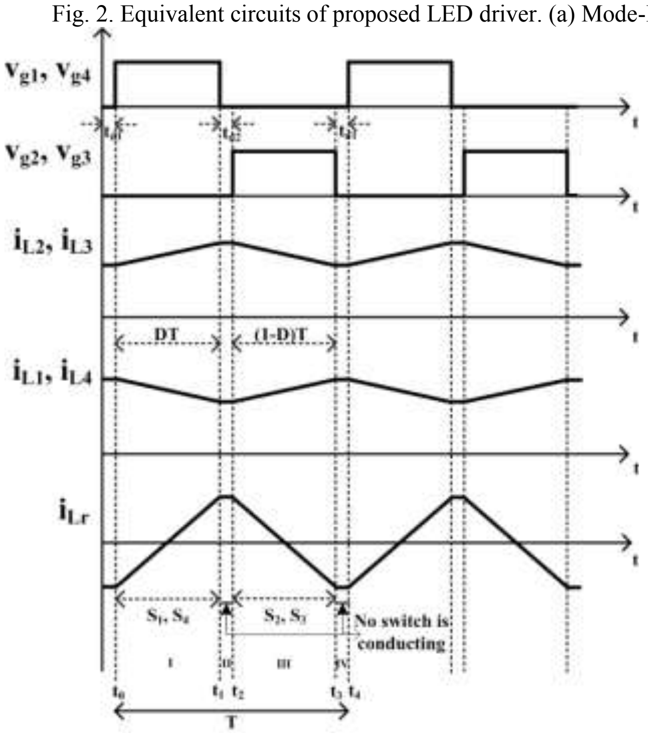


Fig. 3 Operating waveforms of Proposed LED driver.

$$i_{Lr}(t) = \frac{V_{in}}{L_r}(t - t_0) + i_{Lr}(t_0) \qquad t_0 \le t < t_1 \qquad (4)$$

In mode-III, the LED lamp-2 is supplied by the stored energy in the inductor L_2. The corresponding equivalent circuit is shown in Fig. 2(c).

The voltage across inductor L_2 is

$$v_{L2} = -V_{02} = L_2 \frac{di_{L2}}{dt} \qquad t_2 \le t < t_3 \qquad (5)$$

The current through the inductor L_2 is expressed as

$$i_{L2}(t) = \frac{1}{L_2}\int_{t_2}^{t} v_{L2}(t)\,dt + i_{L2}(t_2) = \frac{-V_{02}}{L_2}(t - t_2) + i_{L2}(t_2) \qquad t_2 \le t < t_3 \qquad (6)$$

where $i_{L2}(t_2)$ is the initial current in the inductor L_2 at time $t = t_2$.

The ripple current in inductor L_2 is expressed as

$$\Delta i_{L2} = i_{L2}(t_3) - i_{L2}(t_2) = \frac{-V_{02}}{L_2}(1 - D)T \qquad (7)$$

During this interval, voltage across L_r is $-V_{in}$. The current through it decreases linearly and is given by

$$i_{Lr}(t) = -\frac{V_{in}}{L_r}(t - t_2) + i_{Lr}(t_2) \qquad t_2 \le t < t_3 \tag{8}$$

Under steady state operation, the net change in current through inductor L_2 is zero over the time period T. Hence from Eqns. (3) and (7)

$$[i_{L2}(t_1) - i_{L2}(t_0)] + [i_{L2}(t_3) - i_{L2}(t_2)] = 0 \tag{9}$$

$$\Rightarrow \qquad \frac{V_{in} - V_{02}}{L_2} DT - \frac{V_{02}}{L_2}(1-D)T = 0 \tag{10}$$

$$\Rightarrow \qquad V_{02} = DV_{in} \tag{11}$$

Hence, the voltage across LED lamp-2 V_{02} is D times the input voltage V_{in}. Similar analysis can be applicable to other LED lamps also. Eqns. (3), (7), and (11) are applicable to other LED lamps also. Hence, the ripple current through each LED lamp and voltage across each LED lamp are given by

$$\Delta i_{Lk} = \frac{V_{in} - V_{0k}}{L_k} DT = \frac{-V_{0k}}{L_k}(1-D)T \tag{12}$$

$$V_{0k} = DV_{in} \tag{13}$$

where k = 1, 2, 3, 4

From Eqn. (12) the inductor value can be calculated for specified current ripple.

IV. DESIGN CONSIDERATIONS

To calculate the component values of proposed LED driver, the equivalent parameters of LED lamp are required. According to approximated linear model of LED, it can be denoted by a series connection of dynamic resistance r_d, cut-in voltage V_{th} and an ideal diode. Each LED lamp is comprised of two strings of LEDs which are connected in parallel. Each string consists 10 LEDs which are connected in series. The operating point of each LED is chosen at 3.3 V and 550 mA. Four lamps are used in the proposed work. Therefore the operating point of each LED lamp is 33 V and 1.1A.

From Eqn. (13), input voltage V_{in} is given by

$$V_{in} = \frac{V_{0k}}{D} \tag{15}$$

With $D = 0.5$ and $V_{0k} = 33$ V, the input voltage is calculated as $V_{in} = 66$ V.

Rearranging Eqn. (12),

$$L_k = \frac{V_{in} - V_{0k}}{\Delta i_{Lk}} DT \tag{16}$$

With V_{in} = 66 V, V_{0k} = 33 V, D = 0.5, T = 5 μs, peak to peak LED current Δi_{Lk} of 13%, the value of inductor L_k is calculated as $L_k \cong 577\,\mu$H.

An appropriate current magnitude is needed to obtain zero-voltage switching during dead time. In the proposed work constant current during dead time is provided by the inductor L_r. The peak current through L_r is considered to be constant during dead time. At t = t_1, $i_{Lr}(t)$ reaches its value and from Eqn. (4) it is expressed as,

$$i_{Lr-pk} = \frac{V_{in} T}{4L_r} \tag{17}$$

The value of i_{Lr-pk} is inversely proportional to the value of inductor L_r for a constant value of V_{in} and T. For L_r = 120 μH, V_{in} = 66 V, T = 5 μs, i_{Lr-pk} is calculated as $i_{Lr-pk} = 0.6875$ A.

The value of switch output capacitors is also required to get ZVS during dead time. Considering that dead time $t_{d1} = t_{d2} = t_d$, current flowing through output capacitors during t_{d1} or t_{d2} is given by

$$i_{Lr-pk} + \Delta i_{Lk} = \frac{2C_j V_{in}}{t_d}, \; j = 1, 2, 3, 4 \tag{18}$$

From Eqn. (18), the value of switch output capacitor is obtained as

$$C_j = \frac{(i_{Lr-pk} + \Delta i_{Lk})(t_d)}{2V_{in}}, \; j = 1, 2, 3, 4 \tag{19}$$

For i_{Lr-pk} = 0.6875 A, Δi_{Lk} = 13%, t_d = 100 ns, and V_{in} = 66 V, the value of C_j is calculated as $C_j = 629\,p$F.

To get the zero voltage switching within 100 ns the switch output capacitor C_j must be less than 629 pF. If Cj greater than 629 pF keeping the same values, it cannot completely discharge within 100 ns. Thus zero voltage switching (ZVS) may be effected.

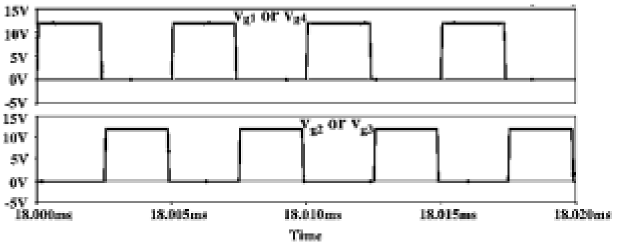
V. DIMMING CONTROL AND CURRENT REGULATION

The essential requirement of the present LED applications is dimming. Dimming can be realized by amplitude modulation (AM) or pulse width modulation (PWM). In AM, dimming is achieved by varying dc current through LED strings. As LED current is not constant, AM dimming is not widely used due to chromaticity variation and nonlinear dimming range. These limitations are overcome by PWM dimming methods. Here, without changing operating current, the illumination level is controlled by switching on and off the LED at a low frequency. These methods feature linear dimming range without chromaticity variations and smooth dimming. In the proposed driver circuit, dimming is introduced by an ON-OFF control switch which is connected in series with input dc source. By a low frequency gate voltage, it controls average illumination level of each LED lamp by turning ON and OFF the whole converter.

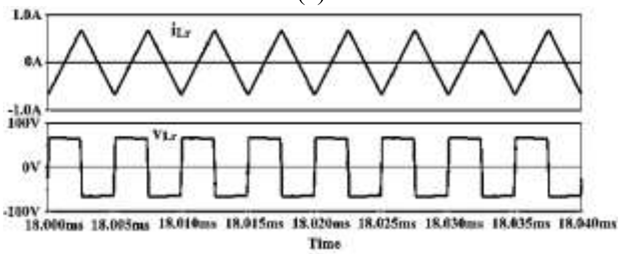
A source converter is connected in series with input dc source as shown in Fig. 1 to regulate LED lamp currents against input voltage variations. This is an essential feature required in battery operated systems. By varying the duty ratio of switch S_B in source converter, the input voltage variations are compensated.

VI. SIMULATION RESULTS

In order to verify the validation of the proposed LED driver, it is simulated using OrCAD PSpice software. The parameters of the proposed driver are given in Table 1. For open loop control of LED brightness, the input voltage to the driver must be maintained constant. This is an unavoidable condition for battery operated or PV operated systems to prevent reduction in LED brightness. For the best adoptability of the proposed LED driver, the dc voltages V_{DC1} and V_{DC2} are taken as 60 V and 12 V respectively. Fig. 4 shows the gate voltages of bridge switches, voltage across L_r and current through L_r. It can be

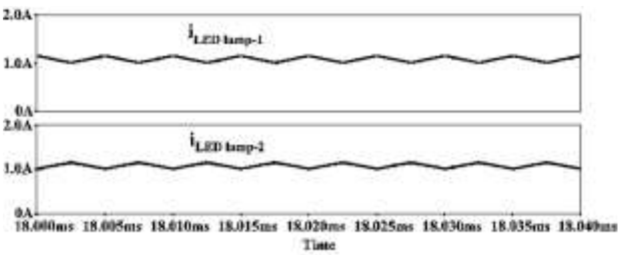


(a)

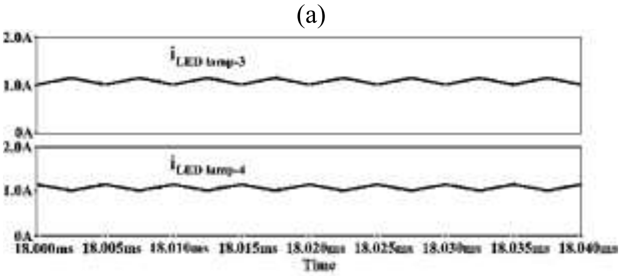


(b)

Fig. 4 (a) Gate voltages of bridge switches. (b) Current flowing through L_r and voltage across L_r



(a)

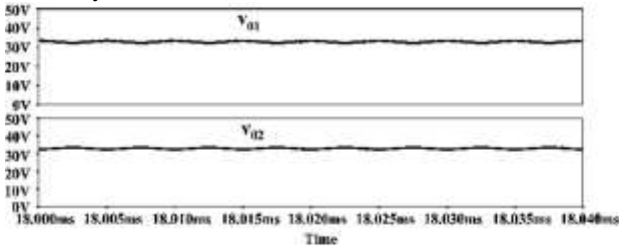


(b)

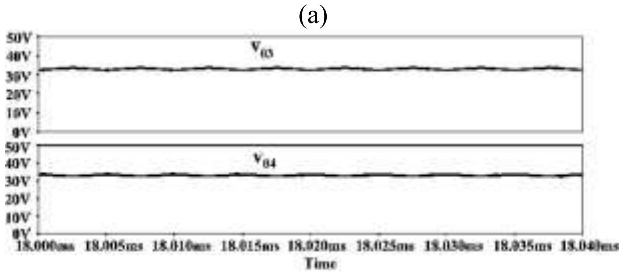
Fig. 5 Current waveforms at full illumination (a) Lamp-1 and lamp-2 current. (b) Lamp-3 and lamp-4 current.

observed that switches in bridge are operated with fixed duty at 200 kHz. The voltage across L_r and current through L_r are in agreement with the theoretical analysis. Fig. 5 shows the current waveforms through all four LED lamps at full illumination level. Fig. 6 shows the voltage waveforms across all four LED lamps at full illumination level. Small ripples are found in LED lamp current and voltages. To verify the soft switching feature of the driver, switch voltage and switch current waveforms are shown Fig. 7(a) and (b). It is noted that switches are switched ON and OFF at zero voltage. Also, switches are carrying only ripple in lamp currents and i_{Lr}. Thus conduction losses are also minimized. Hence the efficiency of the proposed driver is high and efficiency of the driver at full illumination level is found to be 96.88%.

Fig. 8 shows lamp currents at 60% of operating current. It is observed that lamp currents are at their operating values when the dimming switch is ON and they become zero when it is OFF. At this illumination level efficiency is found to be 96.12%.

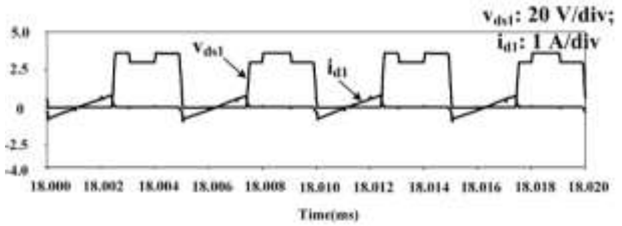


(a)

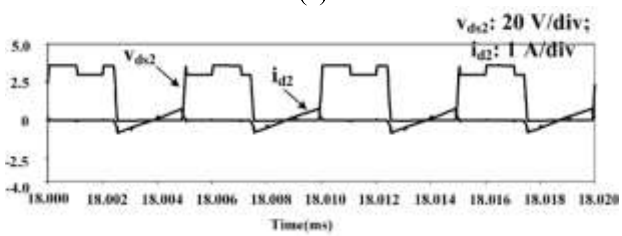


(b)

Fig. 6 Voltage waveforms at full illumination (a) Lamp-1 and Lamp-2 voltages. (b) Lamp-3 and Lamp-4 voltages.



(a)



(b)

Fig. 7 Switching waveforms (a) Voltage and current in Switch S_1 (b) Voltage and current in Switch S_2

Table 1 Parameters of proposed LED driver

DC Input voltage, V_{in}	66 V
Number of LEDs used	80
LED operating current, $I_{operated}$	550 mA
Switching frequency, f_s	200 kHz
Duty ratio of switches in bridge configuration	0.5
L_1, L_2, L_3, and L_4	577 µH
L_r	120 µH
Frequency of source converter	500 kHz
Switching devices used	MOSFET IRF640N

VII. CONCLUSION

In this paper, an efficient LED driver circuit for high power LED lighting systems has been proposed. Zero voltage switching condition is achieved for switches in bridge. And also, switches do not conduct LED lamp currents. Thus both switching and conduction losses are reduced. Dimming is also incorporated for all the LED lamps. Input voltage to bridge configuration is controlled by using a source converter to regulate LED lamp current. A high efficiency is assured at full illumination as well as at dimming level. This driver eliminates output filter capacitor and a rectifier stage. It also reduces component count as well as cost of the driver.

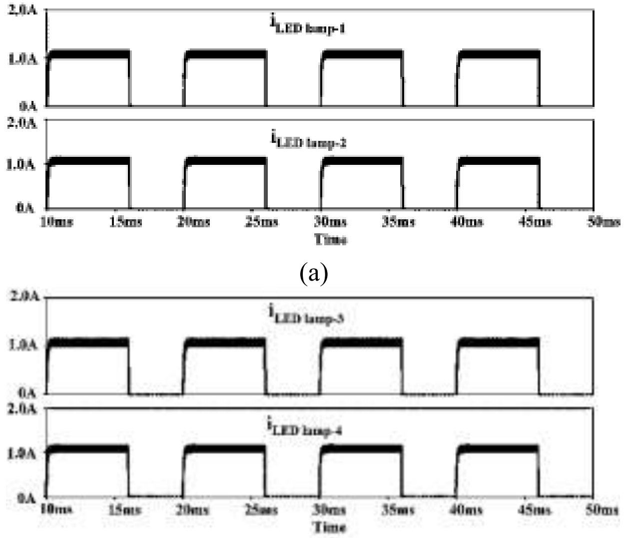


Fig. 8 Current waveforms with 60% of dimming control (a) Lamp-1 and lamp-2 current. (b) Lamp-3 and lamp-4 current.

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