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RESEARCH ARTICLE

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An efficient full-bridge resonant converter for light emitting diode (LED) application with simple current control

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Summary

New power control is introduced in the full-bridge dc-dc converter to drive an LED lamp in this paper. LEDs are semiconductor devices that behave like a constant voltage load with low equivalent series resistance (ESR). Hence, they require precise control for current regulation. In the proposed driver, the LED lamp is driven by two voltage sources connected in series through a series resonant circuit. It processes the majority of lamp power through the full-bridge diode rectifier and supplies small power through a center-tapped rectifier. The LED lamp current is controlled at the selected operating current by using center-tapped rectifier output voltage. In addition, pulse-width modulation (PWM) dimming is implemented. The proposed topology features zero-voltage switching (ZVS), regulation of lamp current, dimming operation, and high efficiency. The working principle, performance, and prototype validation are given for the proposed LED driver.

KEYWORDS

driver circuits, DC-DC resonant converters, light emitting diodes

1 | INTRODUCTION

Lighting systems utilize a considerable portion of total electrical energy generated.[1] Therefore, these systems need efficient light sources. Nowadays, light emitting diodes (LED) have become a promising source of illumination. This is due to their high operating lifetime, higher luminous efficiency, compactness, and good color rendering property.[2-4] At present, LEDs are used in all lighting applications like street lighting, LCD backlighting, traffic lighting, domestic lighting, automotive lighting, parking lighting, and so on.[5,6]

The illumination from LED depends on its forward current. This current must be controlled accurately to obtain the constant light output. Hence, constant current switching regulators are required to drive LED lighting systems at an accurate dc current.[7-9] A good number of ac operated LED driver circuits are available in the literature to meet the essential requirements like high power factor correction (PFC), accurate current control, high efficiency, long life, and dimming features.[10-14] DC operated switched power converters also have been proposed to drive LED lighting systems with precise current control, soft-switching, high efficiency, and dimming capability.[15-19] A three-leg resonant converter to power two LED lamps with different power ratings is presented in Ch Kasi et al.[20] It operates at two different frequencies simultaneously. Besides, two lamps are controlled against input voltage variations, and they can be dimmed independently. In Ch Kasi et al,[21] an LED driver circuit with ripple-free current for high power street lighting applications is proposed. It features ripple-free current in LED lamps, low device current stress, ZVS, and high efficiency. In this configuration, the input voltage is controlled through a buck-boost converter for regulating LED lamp currents. A driver configuration using half-bridge inverter is presented to drive LEDs with zero-voltage switching (ZVS) in Alonso et al.[22] It utilizes a variable inductor to control the LED lamp current. A CLL resonant converter is proposed for multistring LED application in which the regulation of LED current is realized by controlling its input voltage using a buck converter in Chen et al.[23] Frequency modulation is adopted for controlling LED current in a half-bridge–based LLC resonant converter in Kim et al.[24] A series connection of current regulator and a dc source is presented in Moo et al, Moo et al, and Jane et al,[25-27] to improve overall efficiency. In Liu et al,[28] a valley-fill–based LED driver is proposed for a vehicle LED lighting system using high-frequency ac power which improves efficiency and reduces the size of components. A two-input floating buck converter with variable-off time control is presented to realize accurate LED current control in Liu et al.[29] In Hwu and Jiang,[30] LED currents are regulated using a current sharing capacitor.

This paper proposes an LED driver circuit to meet the essential requirements of LED lighting systems. The simplified circuit depicting the basic operation of this configuration is shown in Figure 1, in which LED lamp is driven by two voltage sources V_1 and V_2. V_1 is a constant dc source that supplies the majority of lamp power, and V_2 is a controlled pulsed dc source that processes small power to LED lamp. Both voltages are generated through full-bridge dc-dc resonant converter. The advantage of this topology is that it operates with a constant duty ratio at fixed frequency which can simplify many design aspects. Moreover, LED lamp current can be regulated by controlling V_2. This driver provides dimming control also which helps in energy savings. This paper is organized as follows. Proposed configuration, principle, and analysis are presented in Section 2. Regulation of lamp current and dimming features are discussed in Section 3. In Section 4, design considerations are presented. Both simulation and experimental results are presented in Section 5. Finally, Section 6 concludes the paper.

2 | PROPOSED CONFIGURATION

2.1 | Description of proposed LED driver

Figure 2 shows the proposed full-bridge resonant converter for LED applications. It consists of a full-bridge inverter, a diode bridge rectifier, and a center-tapped rectifier. Four power MOSFETs S_1, S_2, S_3, and S_4 form a full-bridge inverter. A diode bridge rectifier consists of power diodes D_1 to D_4. The center-tapped rectifier uses diodes D_5 and D_6. These rectifiers are connected in parallel. A series resonant branch with L_r and C_r is connected between terminals A and B as shown in Figure 2. V_{01} is the output voltage of the bridge rectifier, and V_{02} is the output voltage of the center-tapped rectifier. Inductor L_r and capacitor C_r are selected to allow the fundamental component of the inverter output. The current i_r is rectified to power the LED lamp. C_{01} and C_{02} are the filter capacitors. LED lamp is driven by the sum of voltages V_{01} and V_{02}. V_{01} supplies the majority of lamp power. For any variation in input voltage V_{dc}, center-tapped rectifier output voltage V_{02} is controlled through switch S_R. This switch is operating at high frequency. Hence, small filter inductor L_0 is sufficient to reduce the ripple in LED lamp current.

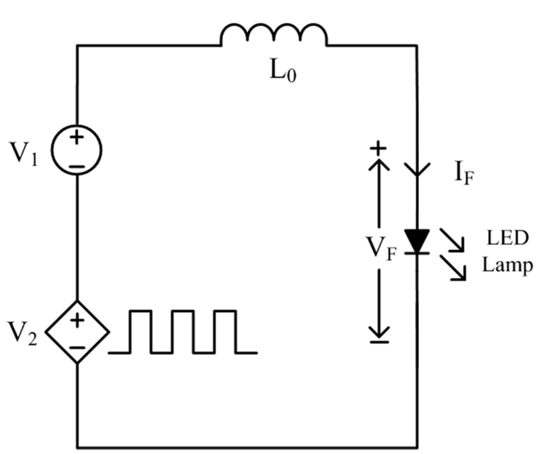


FIGURE 1 Simplified circuit of proposed configuration

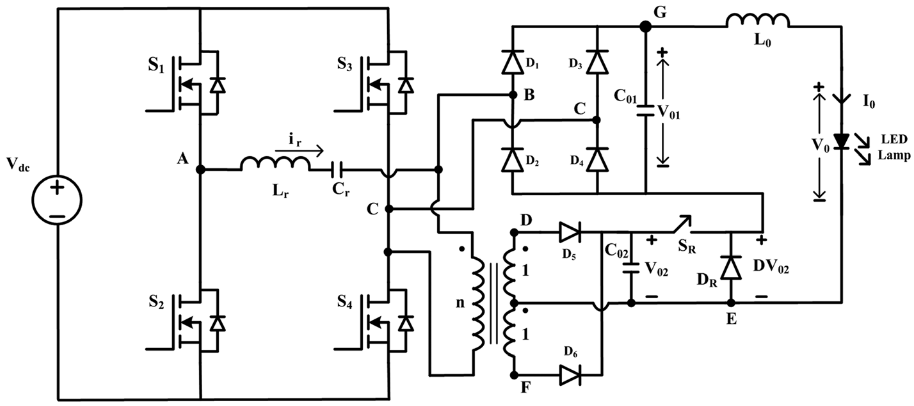


FIGURE 2 Schematic of proposed LED driver

2.2 | Principle of operation

The full-bridge switches are operated at the constant frequency with a duty cycle of 50%. Suitable dead time must be introduced between the gate voltages of each leg to avoid high currents in switches. However, it is not shown in the operating waveforms of the proposed LED driver shown in Figure 3. The switches in full-bridge produce a square wave voltage v_{AC}. The concept of series resonance is utilized for powering LED lamp. A series resonant circuit is formed with

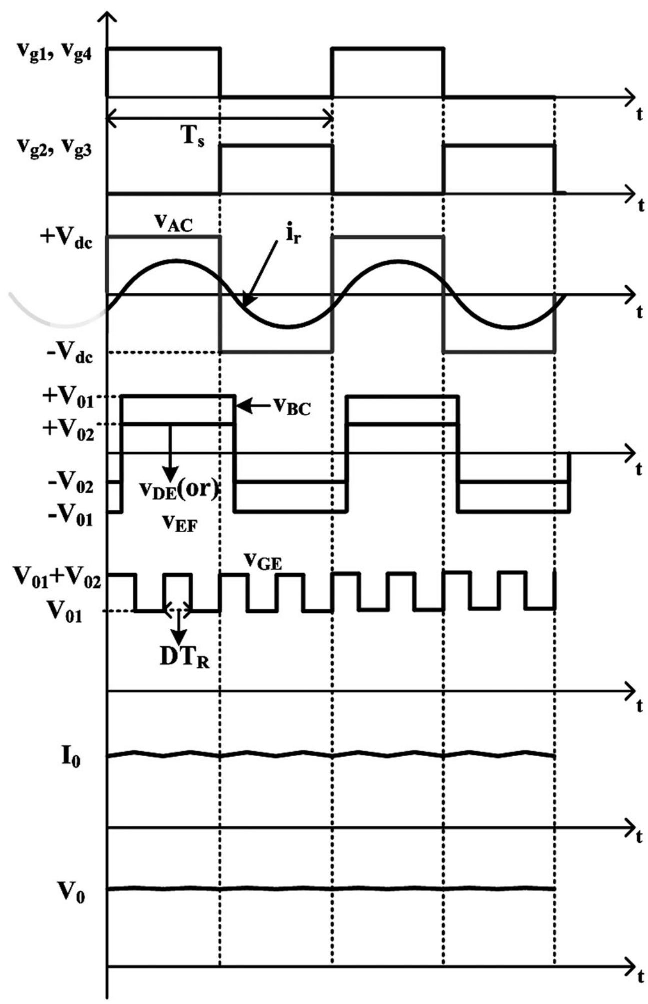


FIGURE 3 Operating waveforms of proposed LED driver

L_r and C_r. It offers low impedance to the fundamental component of v_{AC}. Hence, an alternating current i_r is generated. And it is rectified through both bridge and center-tapped rectifier and filtered to produce voltage V_{01} and V_{02}, respectively. V_{02} is controlled through switch S_R, and a pulsed voltage of magnitude V_{02} is produced across D_R as shown in Figure 2. Hence, the sum of this pulsed voltage and V_{01} is applied to LED lamp. Inductor L_0 is used to provide continuous current through LED lamp.

The advantages of the proposed resonant converter are summarized as follows:

1) Constant switching frequency operation of switches in full-bridge reduces electro-magnetic interference (EMI).
2) Constant duty cycle operation helps in ZVS of switches S_1 to S_4.
3) Ability to regulate the illumination level of LED lamp.
4) Dimming is implemented with a simple pulse-width modulation (PWM) technique.
5) Since series resonance is used for powering LED lamp, it can be designed for high power LED applications.
6) High power conversion efficiency and high-frequency operation reduce the size of LED driver system.

2.3 | Analysis of proposed LED driver

The following assumptions are made to analyze the proposed LED driver:

a) The converter is operating in steady state.
b) All power MOSFETs and diodes are ideal.
c) The voltage across LED lamp is constant.
d) The parasitic components in all passive elements are neglected.

In the proposed configuration, a square wave voltage of magnitude V_{dc} is generated through switching action. And it is applied to the L_r-C_r network that produces a sinusoidal current component. Therefore conventional ac analysis can be used to calculate the static gain of the converter. Figure 4A shows the ac equivalent circuit which can be used to analyze the behavior of the proposed LED driver. The series resonant circuit filters the harmonic voltage components except the fundamental component of voltage v_{AC}. R_{ac} is the resistance seen from the terminals B and C. It accounts for the nonlinearity present in both bridge and center-tapped rectifier. The reactance offered by L_r and C_r are denoted as X_{Lr}

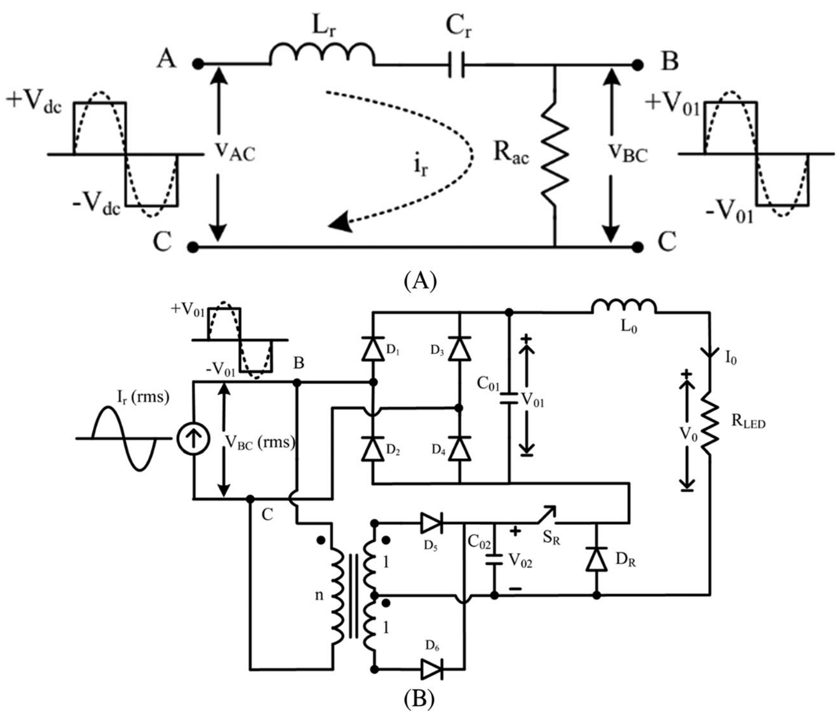


FIGURE 4 A, AC equivalent circuit. B, Equivalent circuit for R_{ac}

and X_{Cr}, respectively. The static gain of the proposed driver can be represented by using a simple voltage division principle as

$$\frac{V_{BC}}{V_{AC}} = \frac{R_{ac}}{R_{ac} + j(X_{Lr} - X_{Cr})} = \frac{1}{\left[1 + j\left(\frac{X_{Lr} - X_{Cr}}{R_{ac}}\right)\right]}. \tag{1}$$

V_{AC} is the fundamental component of the square wave voltage applied to series resonant circuit, and V_{BC} is the fundamental component of square wave voltage of magnitude V_{01}. The ac resistance R_{ac} can be calculated using the circuit shown in Figure 4B. Here, R_{LED} is the resistance offered by LED lamp. The R_{ac} is given by

$$R_{ac} = \frac{V_{BC}(rms)}{I_r(rms)} = \frac{4V_{01}}{\sqrt{2}\pi} \Big/ \frac{\pi I_0}{2\sqrt{2}} = \frac{8}{\pi^2}\frac{V_0}{I_0} = \frac{8}{\pi^2}R_{LED}. \tag{2}$$

The sharpness in the series resonant current is measured by quality factor (Q), and it is defined by

$$Q = \frac{\omega_0 L_r}{R_{LED}} = \frac{1}{\omega_0 C_r R_{LED}} \tag{3}$$

where ω_0 is resonant frequency in radians per seconds, and it is given by

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{L_r C_r}}. \tag{4}$$

Therefore, resonant frequency in hertz is represented as

$$f_0 = \frac{1}{\left[2\pi\sqrt{L_r C_r}\right]} \tag{5}$$

and,

$$X_{Lr} = 2\pi f_s L_r \tag{6}$$

$$X_{Cr} = \frac{1}{2\pi f_s C_r}. \tag{7}$$

By substituting Equations (2), (3), (6), and (7) in Equation (1), the gain is expressed as

$$\frac{V_{BC}}{V_{AC}} = \frac{{}^4V_{01}/_{\pi}}{{}^4V_{dc}/_{\pi}} = \frac{V_{01}}{V_{dc}} = \frac{1}{\left[1 + j\frac{\pi^2}{8}Q\left(\frac{f_s}{f_0} - \frac{f_0}{f_s}\right)\right]}. \tag{8}$$

3 | REGULATION OF LED LAMP CURRENT AND DIMMING CONTROL

To achieve constant illumination from LED lamp, its operating current and voltage must not vary. In the proposed configuration, the variation in input voltage V_{dc} changes the operating voltage and current of the LED lamp. Consequently, lumen output from the LED lamp changes. Therefore, lamp current needs to be regulated against variation in input dc voltage V_{dc}. In this converter, to regulate lamp current against input voltage variations, a pulsed dc voltage of magnitude V_{02} is generated. This voltage is controlled and added with V_{01} to supply the required operating voltage and current of LED lamp.

Dimming is an important feature for present LED applications. It saves a considerable amount of power. A good number of dimming methods are available in literature, such as amplitude modulation (AM),[31] PWM,[32] double PWM,[16,19,25,27] bilevel current control,[33] pulse current control,[34] multiphase PWM,[35] on-off control,[17] etc. All these methods have their own merits and demerits. In the proposed study, PWM dimming is implemented for LED lamp.

To realize PWM dimming in LED lamp, the input voltage to the series resonant circuit v_{AC} is made zero by dimming signal S_{dim}. Hence, average illumination from LEDs is controlled without changing the operating voltage and current. The dimming signal, voltage v_{AC}, LED lamp voltage, and current are shown in Figure 5A.

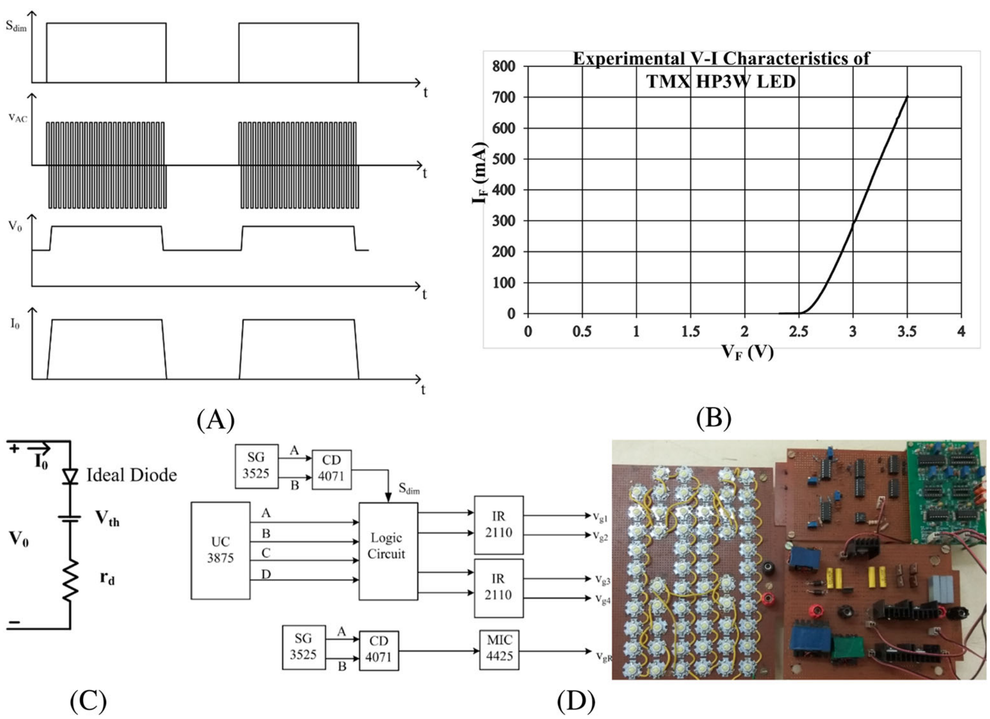


FIGURE 5 A, Dimming signal, input voltage to series resonant circuit and LED lamp voltage and current. B, V-I characteristics of TMX HP3W LED. C, Simulation model of LED lamp. D, Schematic of switch control and experimental prototype [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Parameters of the proposed LED driver

DC input voltage, V_{dc}	48 ± 5% V
Switching frequency, f_s	175 kHz
Resonant frequency, f_0	153 kHz
Resonant inductor L_r	33 μH
Resonant capacitor C_r	0.033 μF
Filter capacitor C_{01} and C_{02}	1.36 μF
Filter inductor L_0	50 μH
LEDs used	TMX HP3W
V_0	49.5 V
I_0	2.24 A
P_0	110 W
Center-tapped transformer	n = 3; PQ 26/25 core
Frequency of switch S_R	400 kHz
PWM dimming frequency	100 Hz
Switching devices used	IRF 540 N
Power diodes used	MUR 860
Control ICs used	UC 3875 and SG 3525
Driver ICs used	IR 2110 and MIC 4425

4 | DESIGN ASPECTS

The LED approximated model[32] is considered to select the component values of the proposed driver circuit. In LED lamp, four parallel strings are used. In each LED string, 15 LEDs are connected in series. The operating point for each LED is selected at 3.3 V, 560 mA. And the cut-in voltage of each LED is 2.32 V. Therefore, operating voltage and current of LED lamp are 49.5 V and 2.24 A. The total power consumed by LED lamp is 110 W.

4.1 | Calculation of series resonant circuit parameters

The product of L_r and C_r is obtained from Equation (5), and it is expressed as

$$L_r C_r = \left[\frac{1}{2\pi f_0}\right]^2. \tag{9}$$

For ZVS, the f_s/f_0 ratio is to be around 1.1. With $f_s/f_0 = 1.14$ and switching frequency f_s of 175 kHz, f_0 is selected as 153 kHz. Now, Equation (9) is expressed as

$$L_r C_r = 1.082 \times 10^{-12}. \tag{10}$$

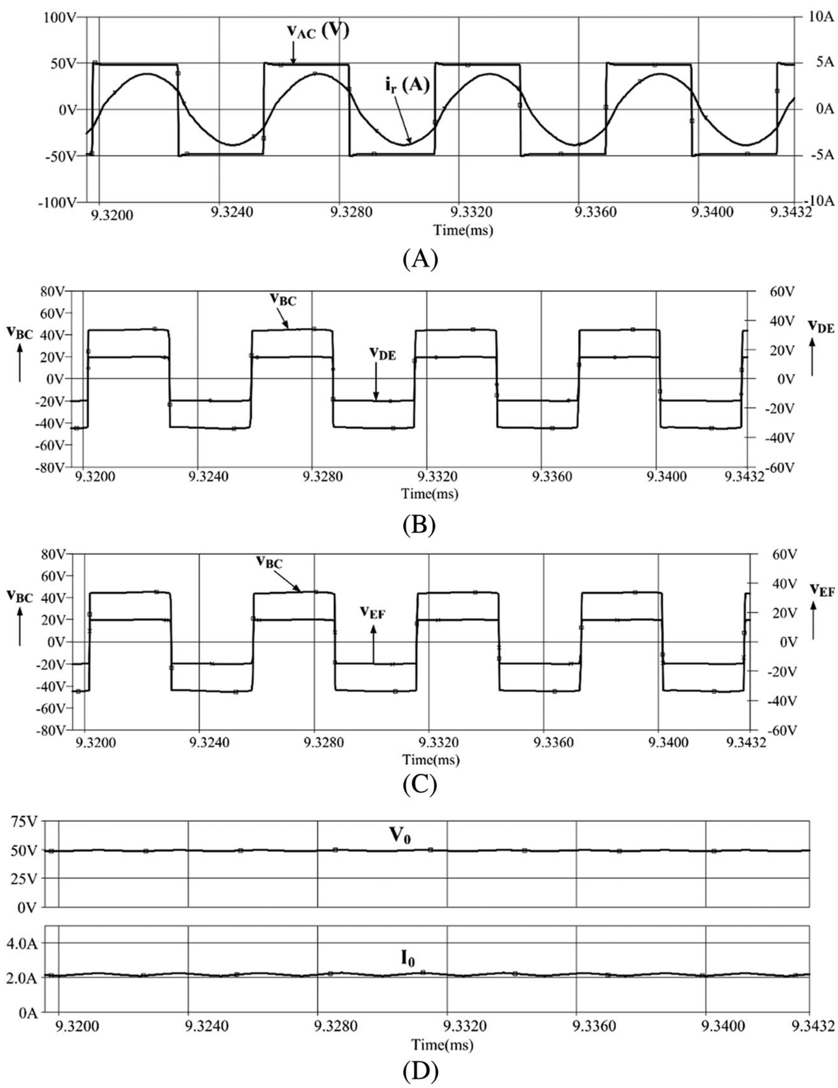


FIGURE 6 Simulated waveforms at full illumination. A, Full-bridge inverter voltage v_{AC} and resonant current i_r. B, Transformer primary and secondary voltages. C, Transformer primary and tertiary voltages. D, LED lamp voltage and current

From Equation (3), quality factor Q is expressed as

$$Q = \frac{1}{R_{LED}}\sqrt{\frac{L_r}{C_r}}. \quad (11)$$

With Q = 1.43 and R_{LED} = 22.09 Ω, from Equations (10) and (11), the inductor L_r and capacitor C_r are calculated as 33 μH and 33 nF, respectively. To allow less than 1% ripple in V_{01} and V_{02}, a value of 1.36 μF is selected as C_{01} and C_{02}. And to allow ripple current less than 10% of I_0 in LED lamp, L_0 of 50 μH is selected.

4.2 | Calculation of output voltage V_{01} and V_{02}

From Equation (8), V_{01} is expressed as

$$V_{01} = \frac{V_{dc}}{\left[1 + j\frac{\pi^2}{8}Q\left(\frac{f_s}{f_0} - \frac{f_0}{f_s}\right)\right]}. \quad (12)$$

With V_{dc} of 48 V, Q of 1.43, f_s of 175 kHz, and f_0 of 153 kHz, V_{01} is calculated from Equation (12) as, $V_{01} \cong 43.5V$.

The operating voltage of the LED lamp is selected as 49.5 V. Remaining 6 V is supplied through a center-tapped rectifier. To supply this voltage, V_{02} of 14 V is generated through a center-tapped transformer with turns ratio of n = 3. Therefore, the duty ratio of switch S_R is 0.42 under normal operating condition.

5 | SIMULATION AND EXPERIMENTAL RESULTS

To validate the proposed configuration for LED applications, 110-W prototype has been implemented. The experimental prototype has been verified through the obtained results from OrCAD PSpice software. The parameters used in the proposed LED driver are shown in Table 1. In the experimental study, TMX HP3W LEDs are used. The experimental V-I characteristics of TMX HP3W LED are shown in Figure 5B. The equivalent parameters of the simulation model of LED lamp, which is shown in Figure 5C, are calculated using experimental V-I characteristics. Schematic of switch control and experimental prototype of proposed LED driver are shown in Figure 5D. LED lamp is powered with input voltage V_{dc} = 48 V at full illumination. Both simulated and experimental waveforms of full-bridge inverter voltage, resonant current, center-tapped transformer input and output voltages, and LED lamp voltage and current at full illumination

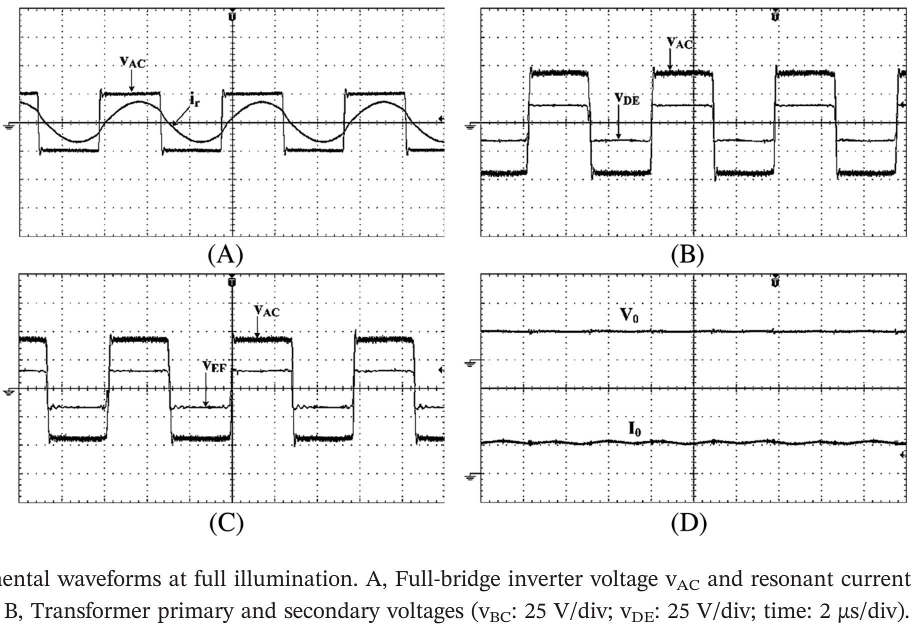


FIGURE 7 Experimental waveforms at full illumination. A, Full-bridge inverter voltage v_{AC} and resonant current i_r (v_{AC}: 50 V/div; i_r: 5 A/div; time: 2 μs/div). B, Transformer primary and secondary voltages (v_{BC}: 25 V/div; v_{DE}: 25 V/div; time: 2 μs/div). C, Transformer primary and tertiary voltages (v_{BC}: 25 V/div; v_{EF}: 25 V/div; time: 2 μs/div). D, LED lamp voltage and current (V_0: 50 V/div; I_0: 2 A/div; time: 2 μs/div)

are shown in Figures 6 and 7, respectively. It is observed that both experimental waveforms and simulated waveforms are in good agreement. To show soft-switching feature in this LED driver, experimental device voltage and current waveforms in one leg of full-bridge are shown in Figure 8. They show that both turn-on and turn-off transition of switches are completed at zero voltage. Hence, switching losses are minimized. Hence, high efficiency is obtained, and it is found to be 93.2% at full illumination level. In this driver, operating voltage and current of LED lamp are maintained constant against the variations in input voltage V_{dc}. And ±5% variation in V_{dc} is considered. During 0 to +5% variation in V_{dc}, the duty ratio of switch S_R is reduced to maintain lamp current at selected value. Similarly, under 0% to −5% variation in V_{dc}, the duty ratio of switch S_R is increased to maintain lamp current constant. Simulation and experimental waveforms of voltage across the series combination of inductor L_0 and LED lamp, and LED lamp current at three different input voltages at full illumination are shown in Figures 9 and 10, respectively. It is observed that the LED lamp is operated at the same operating point with variation in the input voltage of ±5%. And these variations

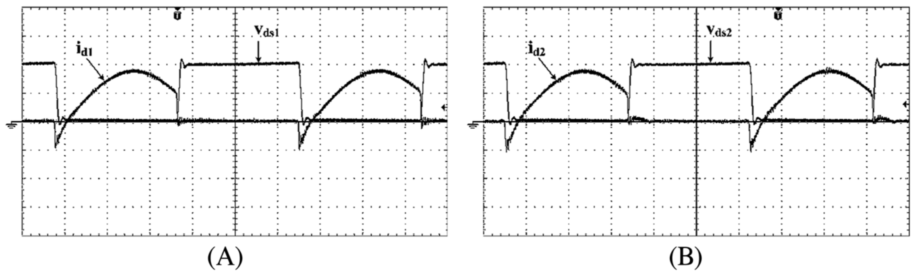


FIGURE 8 Experimental switch voltage and currents. A, Voltage and current in S_1 (v_{ds1}: 25 V/div; i_{d1}: 2 A/div; time: 1 μs/div). B, Voltage and current in S_2 (v_{ds2}: 25 V/div; i_{d2}: 2 A/div; time: 1 μs/div)

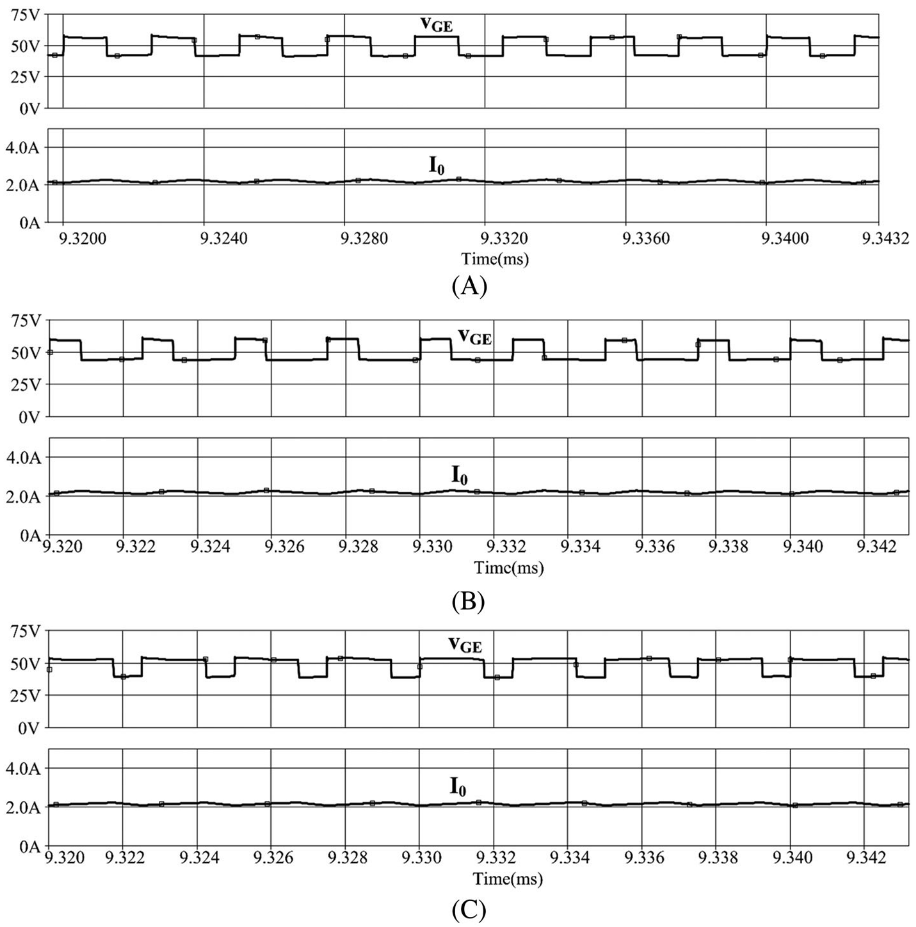
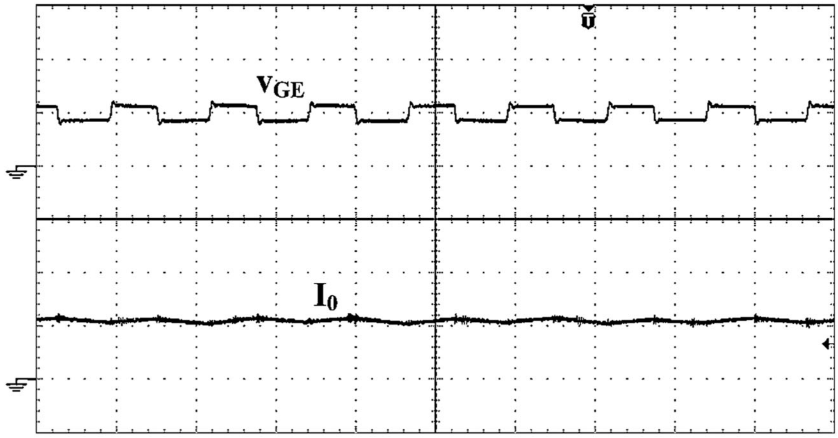
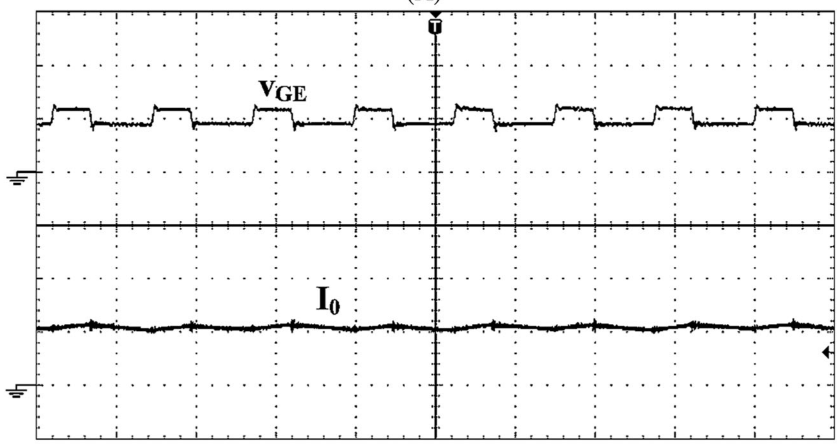


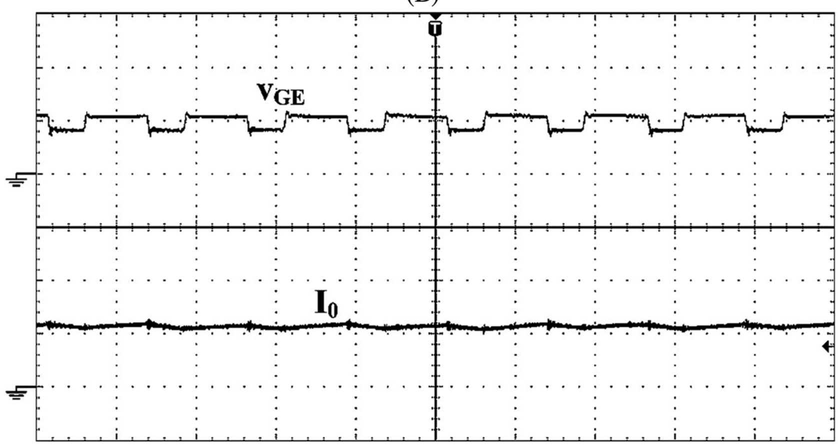
FIGURE 9 Voltage across series connection of L_0 and LED lamp current. A, At V_{dc} = 48 V. B, At V_{dc} = (48 + 5%)V. C, At V_{dc} = (48-5%)V



(A)



(B)



(C)

FIGURE 10 Voltage across series connection of L_0 and LED lamp current. A, At V_{dc} = 48 V. B, At V_{dc} = (48 + 5%)V. C, At V_{dc} = (48-5%)V (v_{GE}: 50 V/div; I_0: 2 A/div; time: 2 μs/div)

do not affect the ZVS conditions of switches in full bridge. Efficiency of 92.4% and 91.8% are obtained with +5% and −5% variation in V_{dc}, respectively.

Figure 11 shows the experimental dimming waveforms of the proposed LED driver at various dimming levels. It is observed from Figure 11B that series resonant circuit input voltage and current are at their rated values when the dimming signal is ON and are zero when the dimming signal is OFF. Similarly, LED lamp voltage and currents are at their operating values when dimming signal is ON, and the LED lamp current becomes zero and LED lamp voltage drops below their cut-in voltage when dimming signal is OFF. The measured efficiency curve of the LED lamp under various dimming levels is shown in Figure 12. It is observed that high efficiency is guaranteed at any dimming level.

A relative comparison among the proposed and LED drivers presented in Ch et al[20,21] is shown in Table 2. It is observed that all the three LED drivers offer high efficiency (>92%), less ripple in LED lamp current, soft-switching operation, dimming control, and good current regulation. All are suitable for high power lighting applications. In

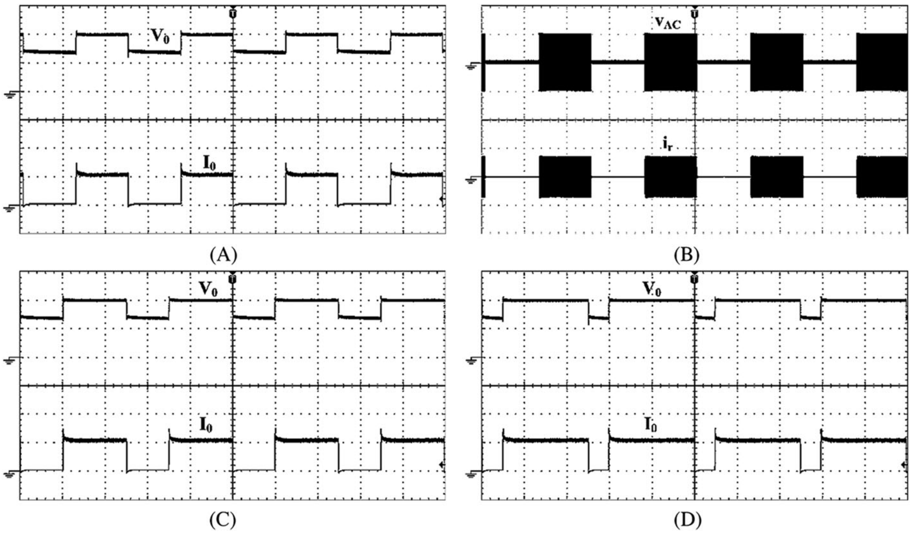


FIGURE 11 Dimming waveforms. A, Lamp voltage and current at 50% of full illumination (V_0: 25 V/div; I_0: 2 A/div; time: 4 ms/div). B, Series resonant circuit input voltage current at 60% of full illumination (v_{AC}: 50 V/div; i_r: 5 A/div; time: 4 ms/div). C, Lamp voltage and current at 60% of full illumination. D, Lamp voltage and current at 80% of full illumination (V_0: 25 V/div; I_0: 2 A/div; time: 4 ms/div)

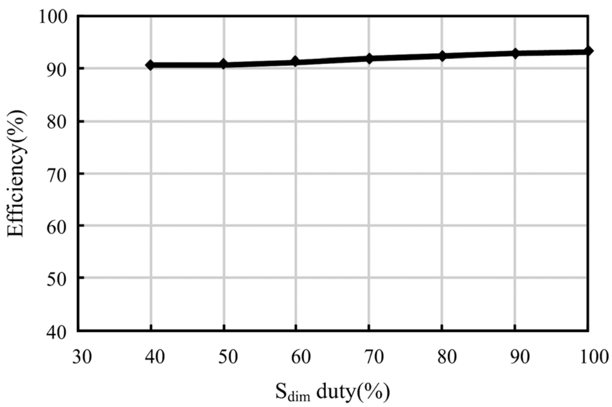


FIGURE 12 Efficiency curve of LED lamp under various dimming levels

TABLE 2 Comparison of the proposed LED driver with LED drivers presented in Ch et al[20,21]

Feature	[20]	[21]	Proposed
Device current stress	Moderate	Very low	Moderate
Ripple in LED lamp	Small	No ripple	Small
ZVS	Partial	Yes	Yes
Total output power	126 W	87 W	110 W
Peak efficiency	92.45%	94.26%	93.2%
LED lamps	2	2	1
Wattage of all LED lamps	Different	Same	Same
Rating of each lamp	Lamp-1 = 86 W and lamp-2 = 40 W	43.5 W	110 W
Dimming	Yes	Yes	Yes
Independent dimming	Yes	No	-
Extension to multiple lamps	Yes	Yes	Yes
Current regulation	Yes	Yes	Yes
High power lighting applications	Suitable	Suitable	Suitable

addition to the above mentioned advantages, each LED driver is having its unique advantages and is suitable for particular applications.

The additional advantage of LED driver presented in Ch Kasi et al.,[20] is that it can control lamps of different wattages. Hence, it is much suitable for domestic and industrial lighting applications. The LED driver presented in Ch Kasi et al.,[21] offers the additional advantage of ripple-free LED current and is suitable for street lighting as well as domestic lighting. The proposed LED driver is suitable for applications where lamp voltages are smaller than the supply voltage. For instance, in dc microgrid lighting applications where the grid voltage level is 380 V. It will offer high efficiency, as the majority of output power is uncontrolled and only small controlled power is used for regulating the lamp current. All three LED driver configurations can be extended to drive multiple LED lamps.

6 | CONCLUSIONS

In this study, a full-bridge resonant converter with a simple current regulation has been developed for LED applications. Switches in bridge operate with constant duty ratio at a constant frequency which does not affect the ZVS conditions. Series connection of two dc voltages supplies required operating voltage and current of lamp. And these voltages are generated by using series resonance. Selected operating voltage and current are maintained constant against the input voltage variations. And also PWM dimming is incorporated. High efficiency (>90%) is achieved at both rated and different dimming conditions. This topology is suitable for applications where lamp voltages are smaller than supply voltages like dc grid applications.

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