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Design of Dimmable Light Emitting Diode Driver for Low Power Applications

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Abstract

High-brightness light emitting diodes (HB-LED) are used in various applications in preference to conventional light bulbs due to following merits: eco-friendly nature, high luminous efficacy, prolonged life, compactness and low heat dissipation. This work presents the boost converter fed dimmable light emitting diode where illumination control is required. The proposed work uses pulse width modulated (PWM) controlled switch in series with LED load to control the illumination level by adjusting the pulse width. The closed loop control is designed in Matlab/Simulink to regulate the load voltage. This paper first illustrates in detail the basic operation of the converter and dimming control and then provides the simulation results with different illumination levels to demonstrate the effectiveness of converter and controller.

Keywords: Light emitting diode; Pulse width modulation; boost converter; closed loop control; illumination

1. Introduction

The electrical lighting technology is in the midst of the biggest and most rapid change in its history. Traditional light sources that have been used for decades are being pushed aside in favor of solid state lighting (SSL). Light emitting diodes is the emerging lighting technology due to its various advantages such as: eco-friendly nature, durability, long life, energy efficiency and compactness [1–4]. Most early power supplies were linear converters. As the technology improved, high-efficiency, small switch-mode power supply driving circuits developed and they are overtaking traditional linear converters. The numerous types of switching converter include buck, boost, buckboost, and Cuk converters, as reported in the literature. The switched mode converter circuit primarily comprises semiconductor switching devices. A DC-DC converter is required to convert the variable DC voltage to constant DC voltage. Some authors proposed DC-DC converter topologies to achieve constant output voltage and high efficiency, and low component count to drive single and multiple outputs simultaneously. Generally, buck converters are widely used as LED drivers due to their simplicity, step-down operation and lower component count [5–7]. However, efficiency decreases when high step-down conversion is desired due to the fact of poor utilization of the switch (lower duty ratio) at the peak value of input voltage. Further, the high-side switch in a buck converter configuration increases the design complexity and cost of the gate driver circuit. A few CIB topologies reported in the literature have a high step-down conversion ratio with increased duty cycle. However, the CI topologies cause high voltage spikes during turn-OFF instant due to the leakage inductance of CI, which leads to subsequent failure of switching devices [8].

Further, the illumination control has not addressed with proposed buck converter. Further, passive clamp techniques are used to minimize/eliminate the switching transients, but with increased cost and complexity. Further, most authors have not addressed illumination control [9–14]. This work presents a closed loop boost converter for dimmable LED lighting applications, which can deliver output voltage regulation, simple gate driver circuit and illumination control. The proposed closed loop dimmable boost LED driver is simulated and analyzed using the Matlab/Simulink platform. A 12 W boost fed dimmable LED driver with closed loop control is built in Matlab/Simulink in order to show the effectiveness of closed loop control.

In this paper, the introduction is followed by section 2, which presents circuit operation and design analysis of the boost converter. Section 3 describes the simulation results respectively. Section 4 presents the conclusions.

2. Operation, Design and Analysis

Fig. (1) illustrates the boost converter fed LED driver which consist of power Mosfet, diode, inductor and output filter capacitor. The boost converters are used to convert the unregulated DC input to a constant DC output at a desired voltage

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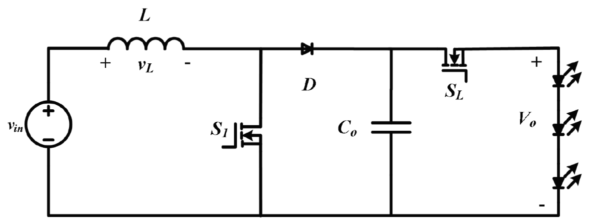

Figure 1: Dimmable boost fed LED driver

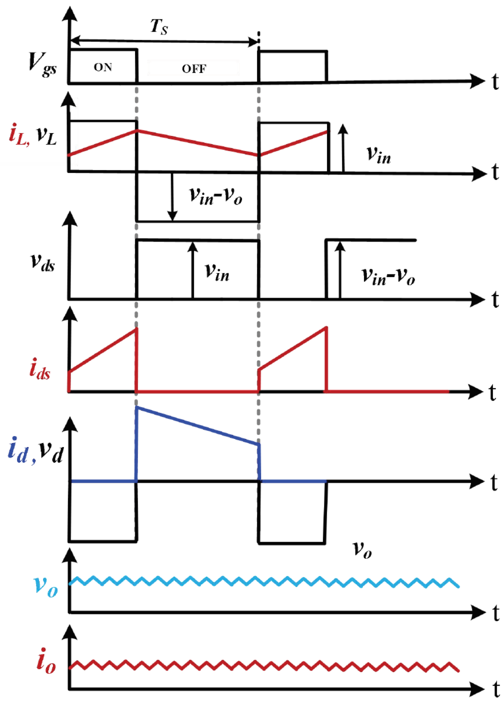

Figure 2: Idealized waveforms of dimmable boost LED driver

level. In this work the boost converter is designed to operate in continuous conduction mode (CCM). Generally, in CCM the inductor current never reaches zero due to the shorter demagnetizing period than magnetizing period. Further in CCM the inductor current has lower peak currents and high efficiency. Fig. (2) depicts the idealized waveforms of the proposed closed loop dimmable boost LED driver. The gating signals are for the main switch (V_{gs}) and dimming switch (V_{gL}) respectively. The duty cycle of the main switch (S_1) and dimming switch (S_L) are defined as $\delta_1$and δ_L, respectively. Moreover, $T_S$represents the switching period of power switches S_1, and $T_L$represents the switching period of dimming switch S_L. To simplify the analysis of the proposed converter, the following assumptions were made.

- All power switches and diodes are ideal.
- In order to maintain constant output voltage, the output capacitors are assumed to be higher values.

2.1. Modes of Operation

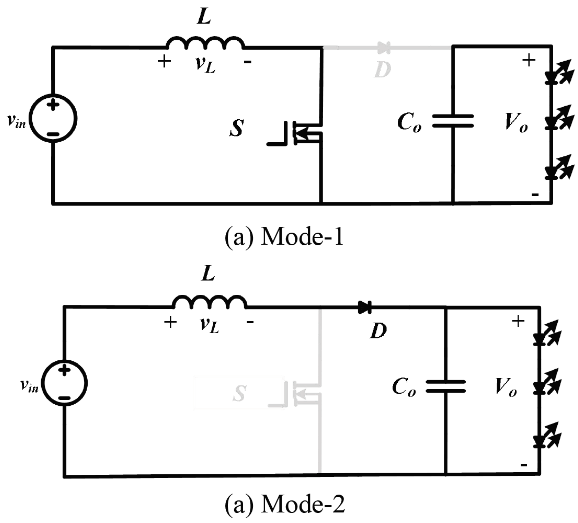

Figure 3: Equivalent modes of boost LED driver

The working principle of a boost converter in CCM is described into two operating modes over a switching period of T_S. Each mode of operation with equivalent circuit representation is illustrated in Fig. (3) (a) and (b) and explained as follows;

Mode-1: Fig. (3) (a) represents the equivalent circuit of mode-1. During this mode of operation the switch is turned-ON for δT_speriod while the diode is reverse biased. This makes the input voltage appear across the inductor and causes the inductor current to start rising linearly. During this mode of operation the capacitor (C_o) alone supplies energy to the load. The voltage across the inductor is described as follows;

$$V_L = V_{in} \Rightarrow (\Delta i_L)_{ON} = \frac{V_{in}}{L}\delta T_s \quad (1)$$

Mode-2: During this mode of operation the switch gets turned-OFF for period of $(1\text{-}\delta)T_s$and diode becomes forward biased to transfer the energy from source to the load. The stored energy in the inductor during turn-ON state and input energy together supplies energy to load and charges the output filter capacitor. As the inductor starts to demagnetize, the inductor current starts to decrease linearly. The equivalent circuit for mode 2 is shown in Fig. (3) (b).

$$V_L = V_{in} - V_o \Rightarrow (\Delta i_L)_{OFF} = \frac{V_{in}-V_o}{L}(1-\delta)T_s \quad (2)$$

By solving the above equations the voltage gain from output terminal to input terminal is obtained as follows:

$$G = \frac{V_o}{V_{in}} = \frac{1}{1-\delta} \quad (3)$$

The minimum inductance required to operate the converter in CCM is obtained as:

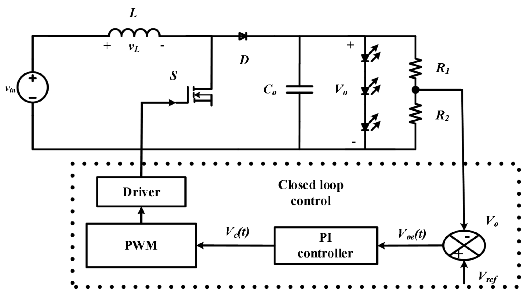

Figure 4: Closed loop voltage mode control boost LED driver

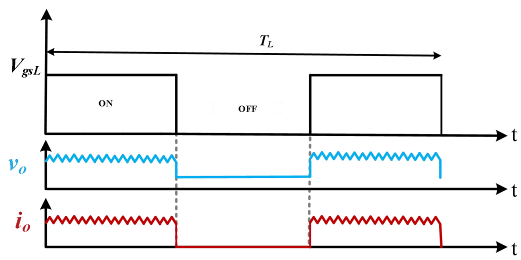

Figure 5: Dimming pulse, output voltage and current of dimmable boost LED driver

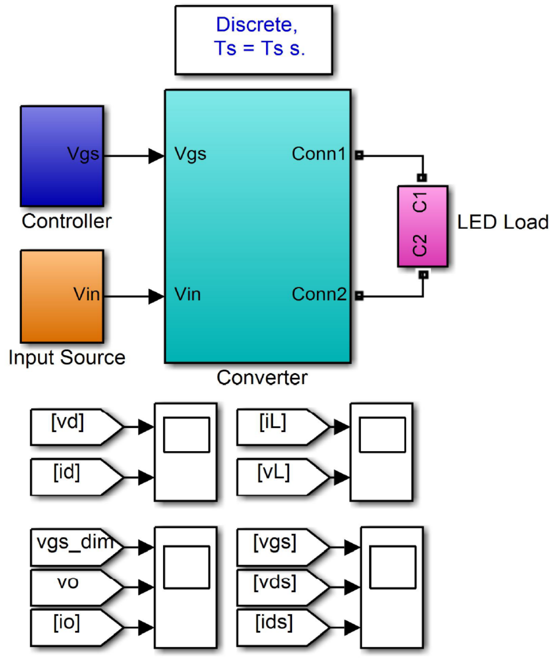

Figure 6: Simulation model of dimmable boost LED driver, open loop model

$$L_{min} \geq \frac{\delta(1-\delta)^2 R_o}{2 f_s} \quad (4)$$

A huge value must be selected for the output filter capacitor (C_o) in order to supply the constant load voltage.

$$C_o \geq \frac{\delta}{R_o(\Delta V_o/V_o) f_s} \quad (5)$$

2.2. Control Scheme

Fig. (4) illustrates a single-loop VMC pulse width modulation (PWM) control strategy for the proposed dimmable LED driver. The VMC based PWM technique is simulated using the Matlab/Simulink environment. In order to control the ON period (T_{on}) of the switch, a closed loop controller is designed. The T_{on}period of the switch is varied with the variation of the source voltage to achieve the desired output voltage for the fixed switching frequency of 50 kHz. For constant switching frequency, when T_{on}changes T_{off}will change accordingly. The control scheme is formed by a proportional-integral (PI) controller and PWM which generates the switching pulses to power Mosfet. A PI voltage controller is designed for voltage loop to achieve good voltage regulations with zero steady state error for line variations.

Dimming control is often needed to control the illumination level of LED light for the human need to create a comfortable environment. Moreover, dimming results in reduced power consumption and produces less heat, hence extends the LED life-span and optimizes running costs. Therefore, dimming control is essential in LED lighting applications. The illumination of LED is directly related to its average current. Amplitude modulation (AM) and PWM methods are used to control the illumination of LED light. AM dimming can be performed by adjusting the duty cycle of the PWM signal, but it leads to color discrepancy due to LED current variation at different illumination levels. Therefore, AM dimming control is not appropriate for an application where constant color stability is an essential requirement. A low-frequency PWM dimming control can be used to prevent color instability of LED light. In order to control the illumination of the proposed dimmable LED driver a low frequency switch is connected in series with the LED load. Fig. (5) illustrates the dimming pulse, output voltage and current of the proposed dimmable LED driver. When the low frequency pulse $V_{gsL}$is high, the dimming switch is in turn-ON condition and load is supplied from the boost converter. When $V_{gsL}$is low, the load is disconnected from the boost converter and the current flow through the load is zero. From Fig. (5), $T_L$and $\delta_L$represent the switching time and duty ratio of the dimming switch respectively. In this way the illumination of LED light is adjusted by controlling the average output current. According to Energy Star Program Requirements Product Specifications for Luminaries, the preferred dimming level is from 35% to 100%.

3. Result and Discussions

Simulation and detailed analysis of the proposed dimmable LED drive shown in Fig. (4) is performed by using the Matlab/Simulink power system toolkit. Table (1) describes the parameters used for simulation studies of the dimmable LED

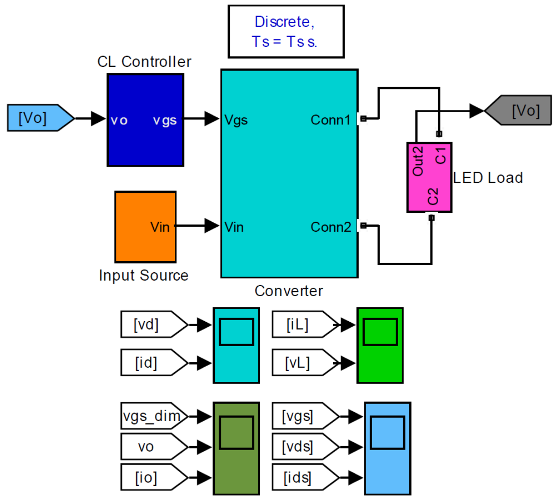

Figure 7: Simulation model of dimmable boost LED driver, closed loop model

Table 1: Specifications used for simulation studies

Parameter description	Value/model no.
Input voltage (v_{in})	12V
Output voltage (V_o)	24V
Output current (i_o)	0.5V
Switching frequency (f_s)	50 kHz
Dimming frequency (f_L)	200 kHz
Inductor (L)	500uH
Capacitor (C_o)	47 µF

driver. The simulation model of open loop and closed loop dimmable LED driver is illustrated in Fig. (6) and (7). Performance analysis of the proposed LED driver was performed with and without a dimming switch, using the Matlab/Simulink environment.

Fig. (8) illustrates the simulation waveforms of gate pulse (V_{gs}), switch voltage (V_{ds}) and switch current (i_{ds}). Fig. (8) and (9) clearly indicate that the switch is turned-ON when the gate pulse is high and the switch is turned-OFF when the gate pulse is low. Fig. (9) shows the simulation waveforms of inductor current (i_L) and inductor voltage (v_L) and they follow the theoretical waveforms presented in Fig. (2). Fig. (9) clearly indicates that the inductor current is always above zero, hence the converter is operating in continuous conduction mode.

The output voltage and output current in open loop operation at input voltage of 12 V is shown in Fig. (10) (a). The output parameters are obtained as per the design parameters. However, the output voltage and current are changing in accordance with the input voltage. The input voltage (v_{in}), output voltage and output current are illustrated in Fig. (10) (b). Fig. (10) clearly indicates that the output voltage and current

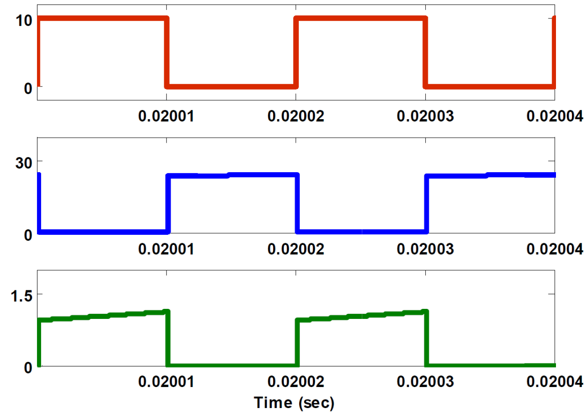

Figure 8: Gate pulse (top trace), switch voltage (middle trace) and switch current (bottom trace)

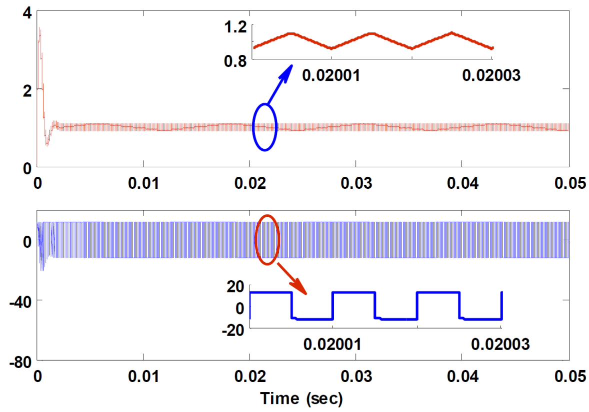

Figure 9: Inductor current (top trace) and inductor voltage (bottom trace)

are changing in accordance with the change in input voltage, which may result in failure of the driver when the current flowing through the LED load exceeds the rated current of LED due to input disturbances. Therefore, in order to maintain output voltage and current constant irrespective of input voltage, a closed loop voltage mode control is developed and simulated in the Matlab/Simulink environment. The output voltage and output current for input voltage variations are illustrated in Fig. (11). Fig. (11) clearly shows that the output voltage and output current are constant for input voltage variations. The output voltage and current are constant at 24 V and 0.5 A.

The dimming control of the proposed dimmable boost LED driver is simulated by connecting a dimming switch in series with the load, as shown in Fig. (4). The output voltage and current for 40% and 80% of dimming is shown in Fig. (12). Fig. (12) shows that the current is flowing through the load when the dimming pulse is high and the load is disconnected from the boost converter when dimming pulse is low, hence no current is flowing through the load. In this way illumination is controlled by controlling the average output current

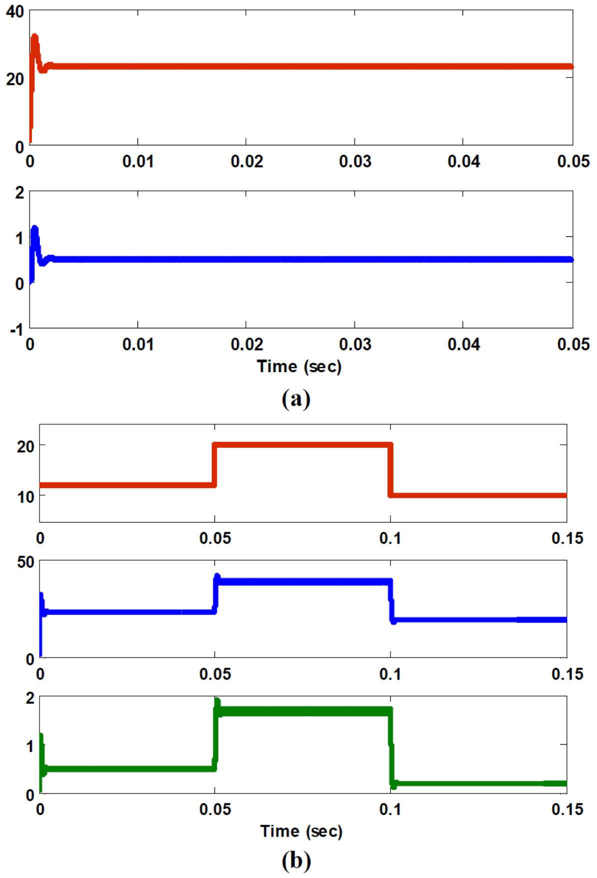

Figure 10: Open loop simulation results; (a) V_o(top trace), i_o(bottom trace); (b) v_{in}(top trace), Vo (middle trace) & i_o(bottom trace)

4. Conclusions

In this paper, dimmable boost LED driver is designed and analyzed in detail. A simulation of a 12 W boost LED driver is developed in both open loop and closed loop control. The results obtained clearly show that the boost converter steps-up the voltage from 12 V DC to 24 V DC in accordance with design parameters. The Matlab simulations using calculated parameters were performed and corresponding waveforms obtained. The output voltage across the capacitor is 24V with a maximum output ripple of less than 1%. The closed loop voltage mode control is validated in the Matlab/Simulink environment to show the effectiveness of the controller. The illumination control of the proposed boost converter is achieved by varying the PWM of a low frequency switch.

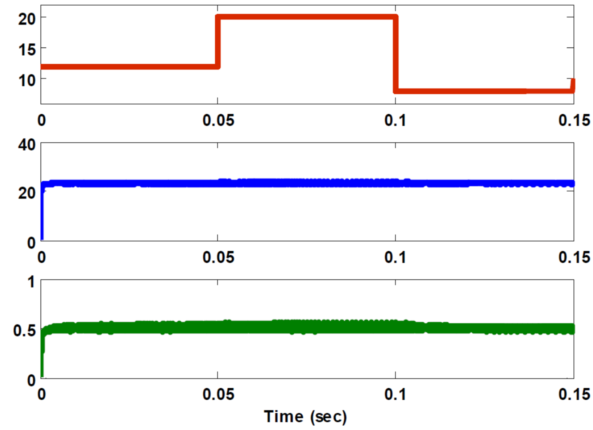

Figure 11: Closed loop waveforms for input variations, input voltage (top trace), output voltage (middle trace) and output current (bottom trace)

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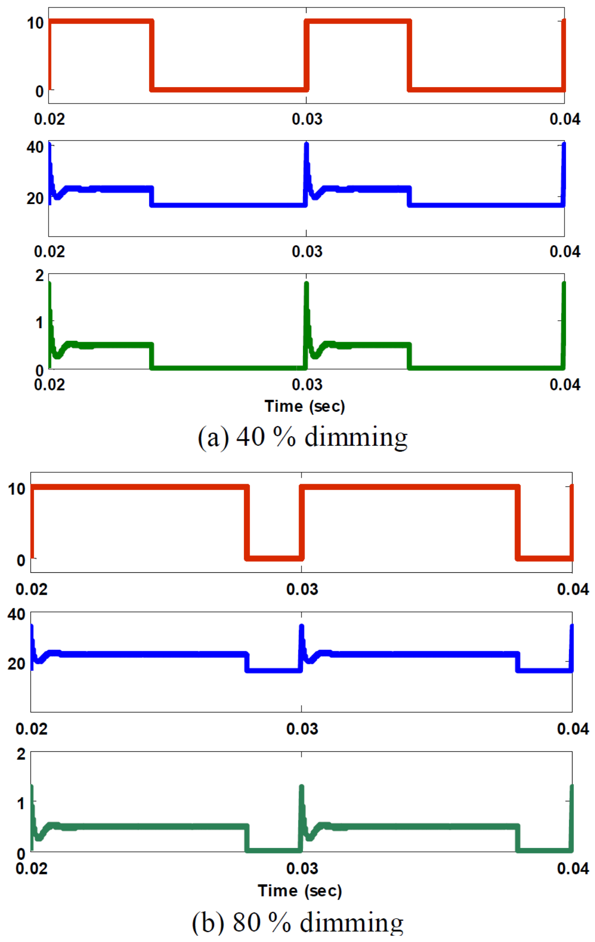

Figure 12: Dimming waveforms dimming pulse (top trace), output voltage (middle trace) and output current (bottom trace)