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Pulse Density Modulation Flyback Converter for LED Automotive Lighting

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Abstract

Switched mode power supply (SMPS) converter is a dc-dc power electronic converter which is used to step up or step down the dc output voltage. A dimmable driver circuit for Light Emitting Diode (LED) lamp for automotive lighting with dimming feature is used in this paper. A flyback converter is used as a driver circuit operated in discontinuous conduction mode to perform dimming control of LEDs. High overall circuit efficiency is achieved by regulating the current through the LED lamps using pulse density modulation scheme. The LED driver circuit design and operating principle is discussed in detail. A gentle current control feature is achieved by pulse density modulation technique. The high performance driver circuit is designed for 25 W LED lamps.

Keywords: *dc-dc conversion, dimming, pulse density modulation, LED driver*

1. Introduction

Light emitting diode’s technology is increasing day by day in general applications because of its longer life, no poisonous content and pollution free with high efficiency related to conventional gas discharging sodium and mercury lamps. LED’s are the new genesis of light source. LED's have different features and properties compared to traditional light source. Normally dc current is used for LED hence special circuit is needed for LED's or ac line voltage can be converted to a small dc voltage at low dc current. As the forward current of LED increases exponentially which depends on biasing voltage, a small fluctuation in voltage will bring a dramatic current and the luminosity variation in LED. Thus a driver circuit is needed for current control. The driver circuit should be designed to operate LEDs at a constant current because LEDs are current controlled devices [1]. The various passive driver circuits employed for low power street lighting applications were reviewed and their performances were compared [2]. Buck converter, boost converter, flyback converter, galvanic isolated resonant converter are discussed for LED applications [3, 4]. Half bridge series resonant inverter circuit was used a current driver for high brightness LED lamps [5]. A Sepic converter with dimmable LED driver was applied for low power applications with power factor correction [6]. A low drop-out (LDO) regulator was presented for outdoor LED decorative lighting applications for robustness and high accuracy [7]. Dimmable driver circuits were employed in automotive applications [8] and flyback converter with dc link was employed [9]. A synchronously rectified flyback converter was employed to drive LED strings with power factor improvement [10]. A single stage forward flyback converter with power factor correction and quasi-resonant control was studied in detail.

A detailed theoretical study on quasi-resonant forward flyback converter was also given and was validated experimentally [11]. Flyback topology is preferred because of its simple design, less components required, no boost inductor and multiple outputs. The properties of the blue light cut-off filter was investigated and a filter was then designed and manufactured to block the blue wavelength region which has shown a unfavorable result to the human eye owing to the spectrum range of the white light LED [12].

This paper discusses a dimming feature LED driver using a simple flyback converter for white LED lamps in which LED’s are stacked in series. The circuit achieves current regulation by pulse density modulation (PDM) which will give high efficiency and eliminates the colour shift.

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2. Research Method

A flyback transformer is a coupled inductor and not true transformer based converter. Figure 1 shows the circuit diagram of a fly-back converter which provides high efficiency driver for LED lamps, which consists of LED's stacked in series. The input voltage is 24V which can be obtained from battery, the driver circuit functions as a current regulator which is formed by a power switch, a coupled inductor and a freewheeling diode. The coupled inductor is shown using the symbol of transformer or a two winding inductor also called as fly-back transformer unlike the ideal transformer [11].

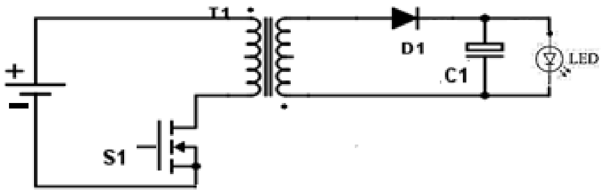

Figure 1. Flyback converter with LED load

In this driver circuit, the capacitor voltage and the LED current are controlled by adjusting the duty ratio of the flyback converter. There will be no transformer action as the primary and secondary winding are coupled. As constant dc (V_{dc}) is applied to the driver circuit primary current I_p rises linearly to the peak value. At this moment, the secondary side is in opposite polarity to the primary winding and thereupon diode. The capacitor provides the load current. When switch is off, the energy stored in the air gap and magnetic core is delivered to the secondary winding and the load is connected to the secondary winding linearly over resistive load.

Energy stored in the air gap can be retrieved from the primary inductance and the primary current is given by [11].

$$E = \frac{1}{2} * L_P * {I_P}^2 \qquad (1)$$

Flyback converter can be operated in two modes: continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The operation of flyback converter is explained as follows: Figure 2 shows the equivalent circuit of the converter when the switch S_1 is ON. Primary current linearly increases and the diode is off state as there is no transformer action. Thus the secondary inductance doesn't exist. At the end of ON time current at primary side reaches to I_{pmax}. Figure 3 shows the equivalent circuit of the flyback converter when the switch S_1 is OFF. During OFF, the magnetizing current stops in the primary winding as the core has to return to its original condition, the voltage at the secondary winding will be reversed for flyback process. This will make the diode to conduct which will decrease the current flow in the secondary winding. Figure 4 shows the characteristics of the flyback converter for DCM and CCM [9]. For DCM the secondary current will become zero for next ON time. For CCM, secondary current will be higher than zero when switch is turned on for next cycle as secondary current will not fully discharged and stored energy will be present on secondary side when next cycle starts.

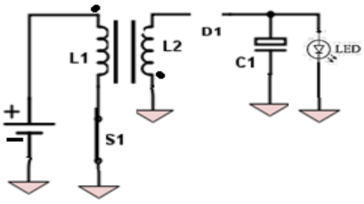

Figure 2. Switch S1 is ON

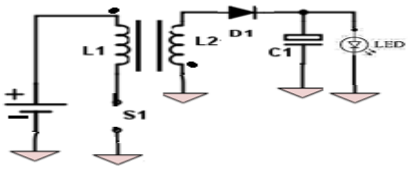

Figure 3. Switch S_1 is OFF

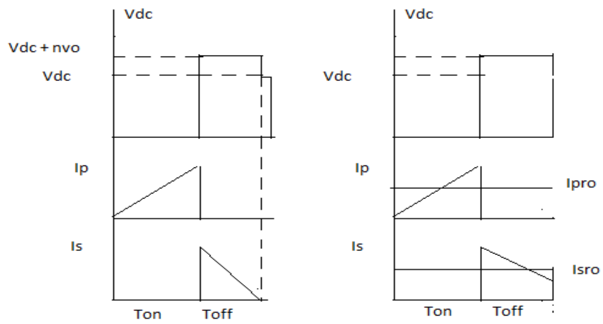

Figure 4. (a) DCM characteristic, (b) CCM characteristic

As the driver circuit will be used for dimming feature the circuit will be used in discontinuous conduction mode.

The luminosity of the LED is approximately proportional to the average current. Dimming can be achieved by both amplitude modulation (AM) and through pulse width modulation (PWM) with the driver used. The amplitude modulation can be done by simply adjusting the duty ratio. But there might be a current variation in LED which may cause color shift. Thus this approach would be inappropriate for dimming application which requires steady color spectrum. To prevent the color shift, PWM for low frequency can be used.

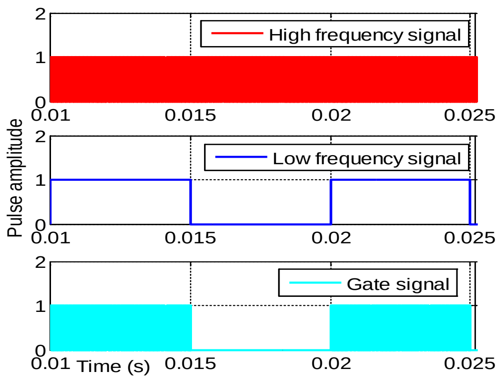

Figure 5. Pulse density modulation control method

Pulse density modulation is used to regulate the amplitude of the pulse current and pulse average synchronously. It is also called as pulse density modulation. Fig 5 reflects the PDM control pattern. A high frequency signal (Vgh) is combined with the low frequency signal (Vgl) to obtain the control pulses. In PDM technique, the flyback converter is in OFF state for a long interval during the low frequency PWM signal. The capacitor will be charged up until the LED lamp cuts off. The LED’s will be in cut off state for long time until the switch is turned on at next cycle. Consequently the LED is driven through a pulsed current. The magnitude of the pulse is governed by high frequency PWM and the average current is controlled by low frequency PWM.

Mode 1: When Switch is ON, current will increase linearly at Ton. From the equivalent circuit shown in Figure 2,

$$V_{lp} = V_{in} \quad (2)$$

$$T_{on} = D.T_p \quad (3)$$

$$I_{lp} = \frac{V_{in}}{L} \times T_{on} \quad (4)$$

When Switch is OFF, Current will drops to zero. From the equivalent circuit shown in Figure 3,

$$V_{lp} = -\frac{V_o}{N} \quad (5)$$

$$T_{off} = (1 - D).T_p \quad (6)$$

$$I_{lp} = 0 \quad (7)$$

Volt second balance rule is applied to derive the transfer function or the voltage gain. Volt second balance: The average voltage across an inductor at steady state must be zero.

$$T_{on} \times V_{lp} = V_{in} \times D \times T_p \quad (8)$$

$$T_{off} \times V_{lp} = -\frac{V_o}{N} \times (1 - D) \times T_p \quad (9)$$

The transfer function of the flyback converter is

$$\frac{V_o}{V_{in}} = \frac{ND}{(1-D)} \quad (10)$$

Steps for designing the flyback converter:
Step 1:- Calculate the output power

$$P_o = V_o \times I_o$$

Step 2:- Calculate the input power

$$P_{in} = P_o/\eta$$

Step 3:- Calculate the average input current

$$I_{in(avg)} = P_{in} / V_{in}$$

Step 4:- Calculate the peak current of primary side

$$I_{in(avg)} = 0.5 \times D \times I_{pk}$$

Step 5:- Calculate the primary inductance

$$V = L \times di/dt$$

$$L_p = V_{in}/ I_{pk} \times T_{on}$$

$$T_{on} = D/Frequency$$

Step 6:- Calculate the turn's ratio

$$N = N_s/N_p = V_o/V_{in}$$

Step 7: Calculate the secondary inductance

$$L_s = N^2 L_p$$

Step 8:- Calculate the magnetizing inductance

$$Lm = K \times \sqrt{Lp \times Ls}$$

Step 9: Calculation of snubber circuit
C_snub=(2 to 10) times the C_{ds}

$$R\_snub = \sqrt{\frac{L_k}{C_{ds}}}$$

There are 24 LEDs with a voltage rating of 3.0 V connected in series. The cut in voltage as per the V-I characteristics of the LED is 2.5 V. The current rating of the LED is 350 mA. LED voltage equation:

$$V_D = I_D R_D + V_\gamma \quad (11)$$

$72 = 0.35R_D + 60$; R_D=34.28 Ω

3. Results and Analysis

The simulation of the circuit is performed in Matlab-simulink environment. The specifications of the flyback converter are given in Table 1. The output voltage and current waveforms are observed for a duty cycle of 10% and 50% in both single pulse width modulation and pulse density modulation. The current and voltage waveforms at different duty cycles in SPWM are shown in Figure 6 and Figure 7. The load current is 46.67% of the rated current for a duty cycle of 10% in SPWM. The rated current is obtained at 50% duty cycle. The current and voltage waveforms for PDM are shown in Figure 8 and Figure 9. The current is 30% for a duty cycle of 10% in PDM. The current and voltage amplitude remains same for a duty cycle of 50% in both methods and operated in discontinuous conduction mode. Above 50%, it is operated in continuous conduction mode.

Table 1. Specifications of Flyback Converter

Variable	Values
Input voltage	24 V
Filter capacitance	110 µF
Output power	25 W
Duty ratio	0.1~0.5
Rated current of single LED	350 mA
Rated power of single LED	1.25W
Switching frequency	50 kHz
Dimming frequency	200 Hz

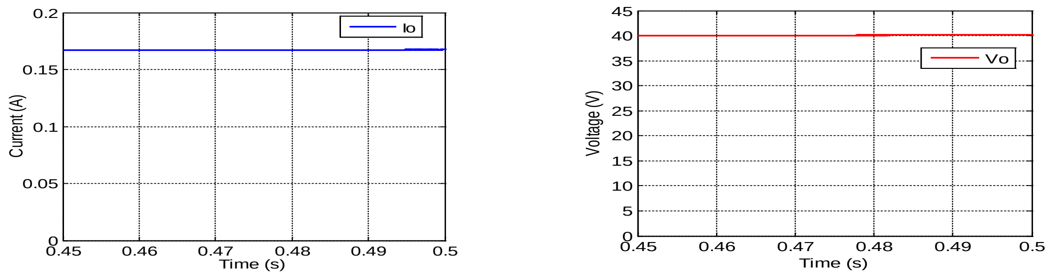

Figure 6. Current and voltage waveforms for 10% duty cycle in SPWM

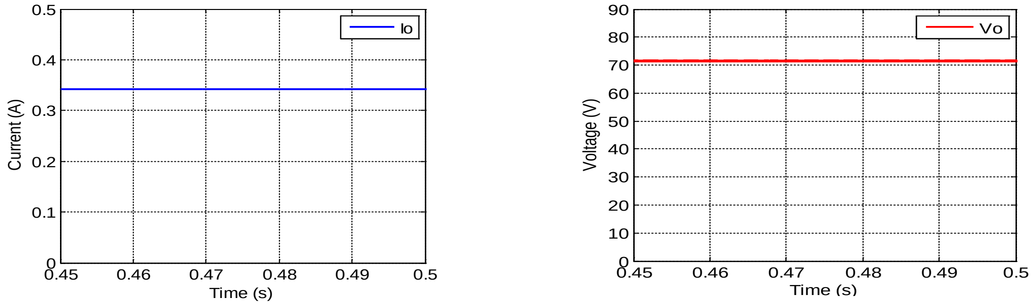

Figure 7. Current and voltage waveforms for 50% duty cycle in SPWM

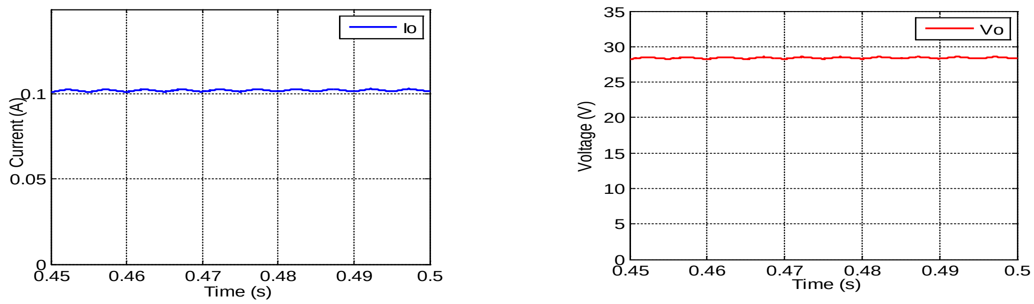

Figure 8. Current and voltage waveforms for 10% duty cycle in PDM

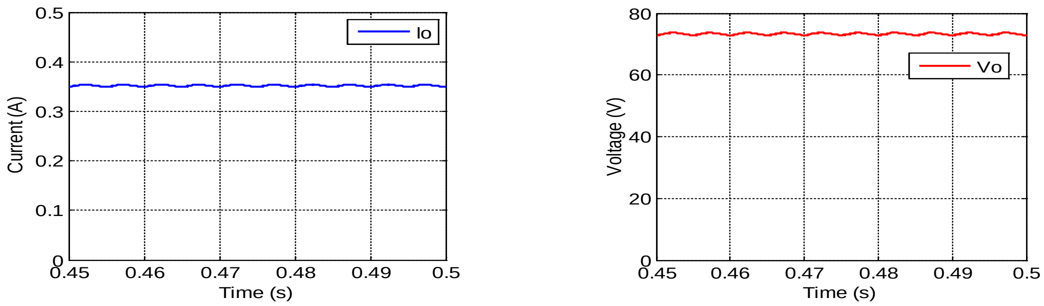

Figure 9. Current and voltage waveforms for 50% duty cycle in PDM

4. Conclusion

A high performance and high luminosity LED driver is discussed. The driver circuit consists of a single power electronic switch and a flyback transformer from which current regulation is achieved by duty cycle control. The dimming feature is attained by PDM. The driver circuit is designed for a 25 W LED lamp and software simulation is performed in MATLAB. The simulation results are provided for different duty cycles to show the effectiveness of the PDM control technique. It can be further extended for LED street lighting for brightness control.

Nomenclatures

V_{in}-Input voltage (V)
V_o-Output voltage (V)
V_{lp}-Voltage across primary inductance (V)
V_{ls}-Voltage across secondary inductance (V)
T_{on}-Turn on time (s)
T_{off}-Turn off time (s)
D-Duty ratio

L_p-Primary inductance (H)
L_s-Secondary inductance (H)
L_k-Leakage inductance (H)
N_p-Number of turns on primary side
N_s-Number of turns on secondary side
N-Turns ratio
K-Coupling coefficient
I_{pk}-Primary current (A)
P_{in}-Input power (W)
P_o-Output power (W)
η-Efficiency of the driver (%)
C_{ds}-Drain to source capacitance (F)

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