The Output Ripple Current of Single-Stage Flyback Converter with High Power Factor in LED Driver

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Abstract

This paper describes analysis and calculation of line frequency ripple current according to output capacitor value and effects of LED connection in the single stage flyback converter with high power factor. The low frequency output ripple current delivered from single stage converter has been analyzed in detail and the method evaluating parasitic resistance included in LED has been provided. In order to verify the equation derived in this paper, the single stage flyback converter has been designed with constant output current regulation with DCM operation. Experiments were conducted with different LED load structures to analyze the effect of LED parasitic resistance on output ripple current. As test results, the calculation can provide guide line to select capacitor values depending on output ripple current and LED characteristics.

Ⅰ. Introduction

In order to reduce CO2 in all over the world, the conventional lamps used commonly as lighting sources are replaced to LEDs because they have very long lifetime and low power consumption compared with incandescent lamp and halogen which converted to light by only 10% electricity of total power flowing through them[1][3]. However, customers want to minimize facilities change for installation of new lamps with LEDs. Therefore, LED lighting lamps should be same type and size with conventional lamps in residential and commercial lighting application. In addition, International Electro-technical Commission (IEC) established the standard Total Harmonic Distortion (THD) as IEC 61000-3-3[2]. Beside, the power factor (PF) of electrical facilities has been more important until recent days. Accordingly, the manufacturing and developing companies of LED lamps prefer to more simple and cost effective LED drivers which meet international standard. That is the reason why the most companies select the single stage flyback converter with high PF for LED driver. However, the single stage flyback converter can't use DC link capacitor to get high power factor. The input voltage that wasn't filtered by DC link capacitor fluctuates from zero to peak level and then delivered to output and cause output current to have big ripple with line frequency. The most designers use big output capacitors to reduce the output current ripple according to customer specifications. In this paper, when single stage flyback converter is used for LED driver, the detailed analysis for the line ripple current according to output capacitors and LED connections is presented. In order to verify results got from analysis, the primary side regulation (PSR) single stage flyback converter was designed and used with FL7732 which operated with constant current (CC) regulation results.

The paper is organized as follows: In section Ⅱ, the single stage flyback converter's configuration and detailed analysis for output current are presented. The experimental results which verify validity of analysis are displayed in section Ⅲ. Finally, the conclusions of line ripple current of single stage flyback converter for LEDs lighting applications are summarized in Section Ⅳ.

Ⅱ. LED Driver

A. Single stage flyback converter

The proprietary topology based on FL7732 enables simplified circuit design for LED lighting applications. 오류! 참조 원본을 찾을 수 없습니다.1 shows the simplified circuit diagram of a primary-side regulated flyback converter including FL7732 operated with CC regulation. By using single-stage topology with primary-side regulation, a LED lighting board can be implemented with few external components and minimized cost, without requiring an input DC link capacitor and feedback circuitry. To implement high power factor and low THD, the constant on-time control utilizes an external capacitor connected at the COMI pins.

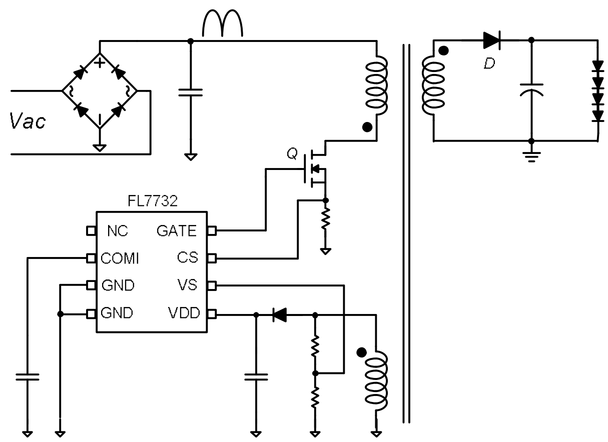


Fig. 1. The simple single stage flyback converter for LED driver

B. Fundamental analysis

Figure 2 illustrates the theoretical waveforms of the primary side switch current, the secondary side diode current and gating signal. The peak inductor current will be enveloped by a rectified AC line voltage. Therefore, the averaged input current will be sinusoidal waveforms and will obtain a good power factor if turn-on time of MOSFET is constant during one line cycle.

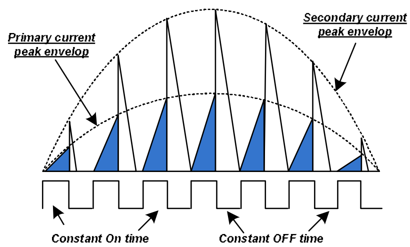
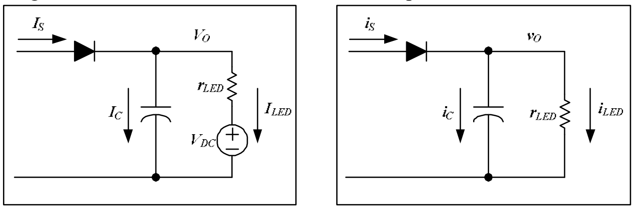


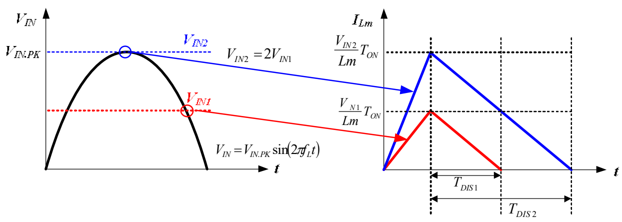
Fig. 2. The current waveforms for MOSFET operation.



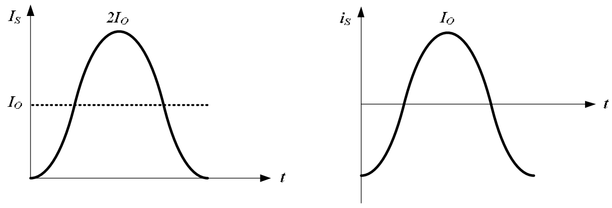
(a) Equivalent Circuit (b) AC Signal Circuit

Fig. 3. Equivalent circuits for real and AC signal analysis

Since LED made of semiconductor materials is not a perfect conductor, some resistance is in series with constant voltage load. This means that the voltage drop will increase with current. ESR (Equivalent Series Resistance) of power LED is different depending on the semiconductor material used but it will roughly inversely proportional to current rating of the LED[6]. Therefore, LED equivalent circuits connected in single stage flyback converter consist of DC voltage source and r_{LED} as shown Fig. 3(a). If AC ripple current was considered only, circuit can be represented as Fig. 3(b).



(a) MOSFET and Diode current of Flyback converter



(b) Averaged diode current (c) AC ripple current

Fig. 4. The MOSFET and diode current waveforms

In Figure 4(a) shows primary MOSFET current and secondary diode current according to input voltage in a single stage flyback converter. When the MOSFET is turn on, the primary of the transformer is directly connected to the input voltage and the MOSFET current increases linearly from zero to the peak value. During this time, the energy is stored in the inductor. When the MOSFET is turn off, the energy stored in the inductor is allowing current to flow from inductor. Then, the diode currents are decreased linearly from peak value to zero. Once single stage flyback converter is operated with discontinuous conduction mode, the relation between averaged primary and secondary current for one line cycle became proportional to square ratio as shown Fig 4. Assuming that rated output current is averaged diode current, it can be estimated as:

$$I_S = 2I_O \frac{1-\cos(4\pi f_L t)}{2} \qquad (1)$$

where, I_O is rated output current. Then, AC ripple current with line frequency can be given as:

$$i_S = -I_O \cos(4\pi f_L t) \qquad (2)$$

$$|i_S| = I_O \qquad (3)$$

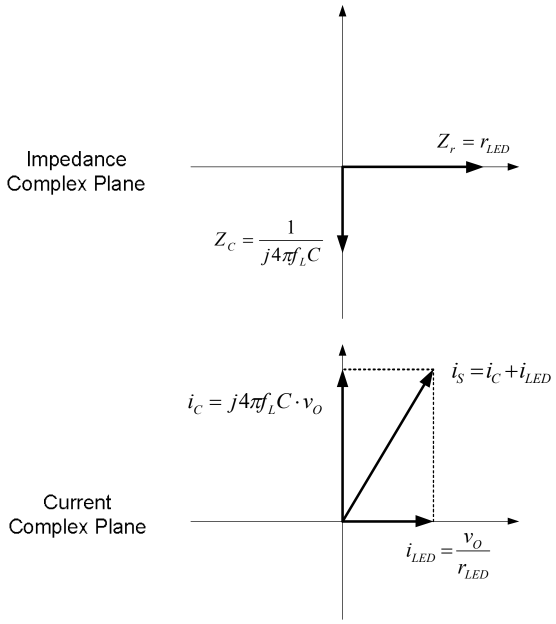


Fig. 5. Complex plane for impedance and current

Figure 5 shows complex plane of the impedance and AC ripple current on equivalent circuits as shown Fig 3. AC ripple current of output current can be calculated as:

$$|i_S| = |v_O|\sqrt{(4\pi f_L C)^2 + \left(\frac{1}{r_{LED}}\right)^2} \qquad (4)$$

Where, v_O is voltage across capacitor or r_{LED} and can rewrite as:

$$|v_O| = \frac{I_O}{\sqrt{(4\pi f_L C)^2 + \left(\frac{1}{r_{LED}}\right)^2}} \qquad (5)$$

The current flow r_{LED} can be obtained by using equation 5.

$$|i_{LED}| = \frac{|v_O|}{r_{LED}} = \frac{I_O}{\sqrt{1+(4\pi f_L C r_{LED})^2}} \qquad (6)$$

Once r_{LED} value is given from LED datasheet, the equation to calculate output capacitor values can be derived as

$$C = \frac{1}{4\pi f_L r_{LED}}\sqrt{\left(\frac{1}{k_{ripple}}\right)^2 - 1} \qquad (7)$$

where k_{ripple} is the ripple percentage for rated output current.

C. Dynamic Resistance of LED.

The dynamic resistance of LED, r_{LED}, is obtained from the I-V characteristic curve provided by LED manufacturers. Figure 6 shows an example of the I-V characteristic curve of EHP-GT01H LEDs of EVERLIGHT. Assuming the output LED current is 720mA and the output voltage is 24V, r_{LED} is the slope of the tangent line at 720mA of LED current. In this case, r_{LED} is about 1.47. To provide the output voltage, 6ea of LED is connected in series. Therefore, the total dynamic resistance of LED string n r_{LED} is 6 times 1.47, i.e. 8.82Ω.

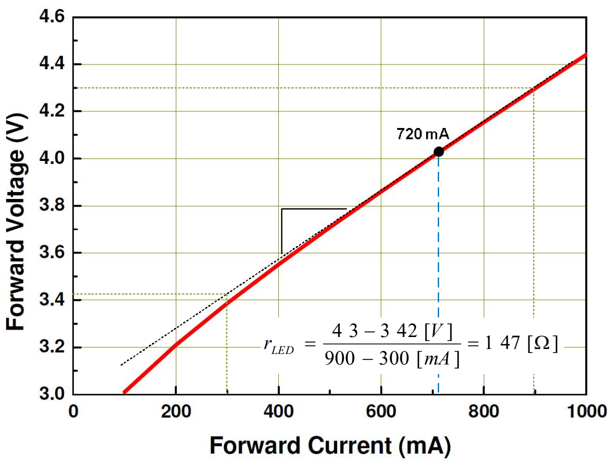


Fig. 6. I-V characteristic curve of LED

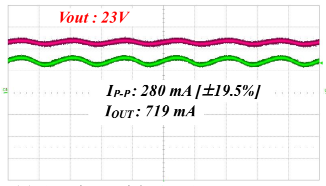
Ⅲ Experimental Results

The system parameters are summarized in Table 2. The tests were conducted by changing LED numbers and series or parallel connection of LED configurations.

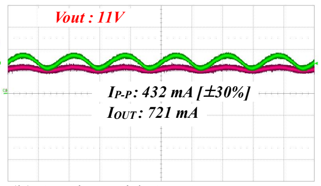
Table. 1. System parameter of LED driver.

Item	Value
Output voltage	24 V
Output current	720 mA
Input voltage	90Vac ~ 265Vac
Line Frequency	60 Hz
Transformer turn ratio	N_P [3] : N_S[1]
Output Cap. measured by LCR meter	810 uF
LED	EVERLIGHT 1W, 3W

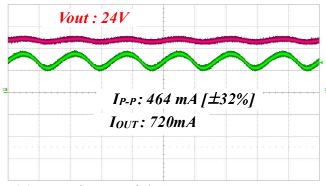
Figure 7 show the experimental waveforms on different LED configurations. Figure 7 (a) and (b) are test results respectively for 6ea and 3ea of 3W LED with one LED string. Figure 7 (c) and (d) are test results respectively for one and two strings connected with several 1W LEDs based on the same output voltage.



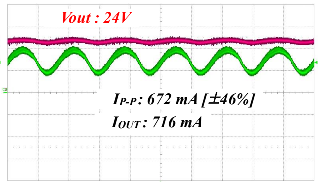
(a) 1 string with 6ea 3W LEDs



(b) 1 string with 3ea 3W LEDs



(c) 2 strings with 12ea 1W LEDs



(d) 3 strings with 18ea 1W LEDs

Fig. 7. Experimental waveforms of output voltage and current

In order to validate proposed analysis, the actual capacitor value used in system can be compared with the capacitor calculated by equation 7 based on the output current ripple percentages measured as Fig. 7 (a). The output capacitor value computed by equation 5 is about 760uF and it presents 6% difference between actual and calculated values. The LED load configurations can affect output ripple current with line frequency due to different r_{LED} values depending on LED ESR and their connections. Test results measured in this experimental are summarized as table 2.

Table. 2. Measured results

LED	Load Configuration	Output Voltage[V]	Output Current[A]	Ripple	
				[mA_{P-P}]	[± %]
1W	3 string	23.08	0.716	672	46.93
	2 string	23.55	0.720	464	32.22
3W	6ea series	22.98	0.719	288	19.47
	5ea series	18.98	0.713	320	22.44
	4ea series	14.9	0.716	384	26.82
	3ea series	11	0.721	432	30.00

Ⅳ Conclusion

In this paper, the analysis and calculation for line frequency output ripple current in single stage flyback converter with high PF are presented. To validate this analysis, the experimental results were compared with the calculated. As test result, the output ripple current is affected by LED connections and types due to different ESR values of LED even though the same capacitor values. The proposed analysis can be used to find out proper LED configuration based on output ripple percentage and capacitor value when LED driver is designed.

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