시비율 제어된 벅 LED 구동기의 설계 및 실험

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Design and Experiment of Duty-Cycle-Controlled Buck LED Driver

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ABSTRACT

A discrete time domain analysis for the duty-cycle-controlled buck LED driver is performed in this paper. Based on the analysis, the design guidelines are derived. Experimental results are presented to confirm the design.

1. Introduction

Over the past few years, light-emitting diode (LED) technology has emerged as a promising technology for residential, automotive, decorative and medical applications. This is mainly caused by the enhanced efficiency, energy savings and flexibility, and the long lifetime. Today, LEDs are available for various colors and they are suitable for white illumination. Up to now, numerous attempts have been made to characterize the current-mode control system[1]-[4]. However, all mentioned modeling approaches are related to voltage regulated converters. Very little work has been done in the area of dynamic modeling for the current regulated LED driver[5].

In this paper, the systematic discrete time domain approach[6]-[7] is adapted to modeling and designing feedback compensator for the duty-cycle-controlled buck LED driver. Root locus analysis is used to derive the design guidelines for the PI gains of the feedback compensator, and experimental results are presented to confirm the design.

2. Design Guidelines

The root locus as a function of the P gain k_p is shown in Fig. 1. Unlike the peak-current-controlled buck LED driver reported in [8], this duty-cycle-controlled buck LED driver is unstable for k_p=0. The eigenvalue λ_1 is dominated by the inductor current state. The transient response of λ_1 after a disturbance is underdamped when k_p is between 0 and 0.6. At $k_p = 0.6$, the system response is critically damped. When k_p is greater than 0.6, the transient response of the inductor current is overdamped. In practical design, it is desirable that the transient response of the system should be critically damped or slightly overdamped to avoid an oscillatory LED current for the start-up and step load change. The system response is critically damped when λ_1 is equal to λ_1. Using the condition of $(a_{11}+a_{22})^2-4(a_{11}a_{22}-a_{12}a_{21})=0$, and considering $k_p>0$, the border equation between the underdamped and overdamped cases can be derived as

$$\frac{k_p}{k_{ni}}=(1-2D)+\sqrt{2(1-D)(S_{ri}\frac{2D}{1-D}-D)} \tag{1}$$

where $S_{ri}=\frac{M_e}{(V_oR_s/L)}\frac{1}{k_{ni}}$.

Using (1), PI gain curve for the critically damped response is shown in Fig. 2. The system response is underdamped when k_p is less than the value on the curve, and overdamped when k_p is greater than the value on the curve. Generally, the boundary value of k_p between underdamped and overdamped responses is increasing with increasing k_{ni} for the same D and S_r. The P gain for non-oscillatory response is determined at the maximum D for a range of operation. Selecting k_p slightly greater than or equal to the value on the curve at the maximum D of an operating range, a satisfactory transient response can be achieved. In other words, when D varies between 0.2 and 0.6, the P gain k_p slightly greater than or equal to 0.8 at $D_{max}=0.6$ can be chosen for k_{ni} =0.2 and $S_{ri}=7.5$. Because designing $k_p$according to the border equation of a lower D results in an oscillatory transient response at D_{max}.

3. Experimental evaluation

For performance evaluations, a prototype converter has been constructed as shown in Fig. 3. The constant switching frequency is 100 kHz. The normal operating range of D in the converter is between 0.2 and 0.6. In the experiment, the ramp peak-to-peak amplitude ΔV is 1.7/3 ≈ 0.567 V, which is generated with $\frac{1}{3}$ of the oscillator peak-to-peak amplitude 1.7 V. The ramp slope M_e is $\Delta V/T_s=0.567X100X10^3$. The control IC is CS3842. S is IRF 840 and D is DSEI12-06A. Here, we use pure-white LEDs, Z-POWER w42182, which has a typical current of 350 mA . This LED forward voltage varies from 3.0V to 4.0V, for a nominal of 3.25 V [2]. The output voltage is approximately (3.25V X 5 LEDs in series) 16.25 V. For $R_s=1\Omega$, S_{ri} is $\frac{M_e}{(V_oR_s/L)}\frac{1}{k_{ni}}=\frac{1.5}{k_{ni}}$ and S_r is $\frac{1.5D}{1-D}$. Setting $k_{ni}=0.2$, S_{ri} is 7.5. From (1), $\frac{k_p}{k_{ni}}$ is

$$(1-2D)+\sqrt{2(1-D)(S_{ri}\frac{2D}{1-D}-D)}=$$

$(1-2X0.6)+\sqrt{2(1-0.6)(7.5X\frac{2X0.6}{1-0.6}-0.6)}$=4.0 for the maximum D=0.6. The designed k_p is selected to be 0.84, which is slightly greater than 0.8 for $k_{ni}=0.2$. The integral gain is $k_i=k_{ni}/T_s=0.2X100X10^3=20{,}000$. The PI gains are distributed throughout the feedback path between the current sense and the comparator input. The gain of LM324 is $\frac{1.2k+7.4k}{1.2k}=7.16$. The function of LM 324 is converting the sensed R_si to the internal reference voltage of the error amplifier. The average value of the output voltage of LM 324 is equal to the reference voltage of the error amplifier input, which is 2.5 V in the datasheet [10]. From the datasheet, the internal gain between COMP and the comparator input is $\frac{1}{3}$. The overall proportional gain k_p and integral gain k_i are $\frac{7.16}{3}\text{X}\frac{R_1'}{R_2'}$ and $\frac{7.16}{3}\text{X}\frac{1}{R_2'C_1'}$, respectively. For the designed integral gain $k_i = 20{,}000$, the values of R_2' and C_1' are chosen to be 12 k and 0.01 μF. For the designed proportional gain $k_p = 0.84$, the value of R_1' is chosen to be 4.2 k.

With five LEDs connected in series, which provides a typical loading voltage of approximately (3.25V X 5 LEDs in series) 16.25 V, the measured LED currents are measured with increasing proportional gain as shown in Fig. 4. As the P gain increases from $k_p = 0.1$to $k_p = 0.84$, the transient response of the LED current changes from underdamped to overdamped response, and then to a slower and poor transient response due to the slower error amplifier state for $k_p = 2.0$. This experimental response shows a good agreement with the prediction of the root locus analysis.

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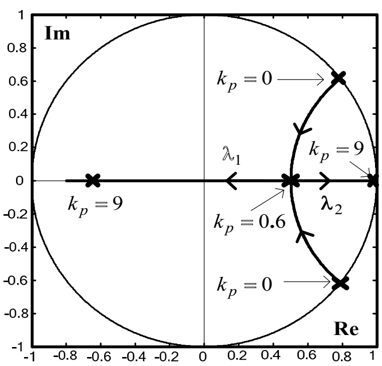


Fig. 1. Root locus as a function of the P gain k_p(k_{ni}=0.2, D=0.45, S_r=0.82)

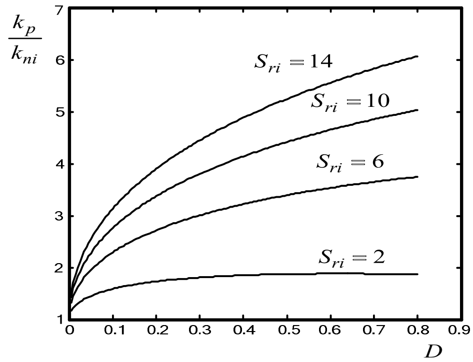


Fig. 2. PI gain curve for the critically damped response

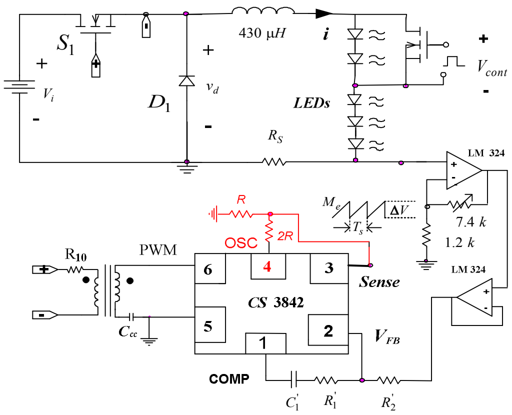
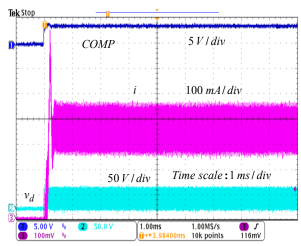
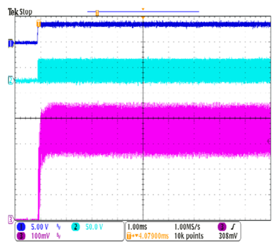


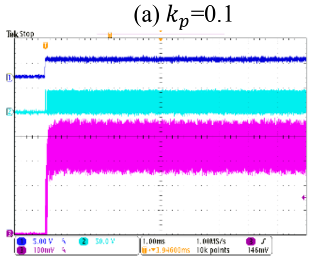
Fig. 3. Experimental circuit



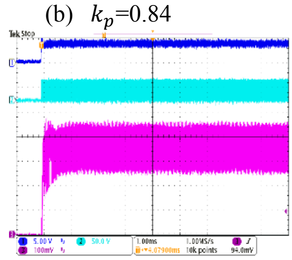
(a) k_p=0.1



(b) k_p=0.84



(c) k_p=1.3



(d) k_p=2.0

Fig. 4. Start-up transient responses with increasing proportionat gain k_p ($V_i = 40V$, $V_o \approx 16.25V$, k_{ni}=0.2)