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

Marn-Go Kim, Young-Seok Jung, and Nam-Ho Kim
Pukyong National University

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 saving, and flexibility, and the long lifetime. Today, LEDs are available for various colors and 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 $\lambda_1$ is dominated by the inductor current state. The transient response of $\lambda_1$ 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 $\lambda_1$ is equal to $\lambda_2$. 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

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

where $S_{ni} = \frac{M}{(\frac{1}{2}V_{in})k_{ni}}$.

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 $S_{ni}$. 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 $S_{ni}=7.5$. 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 $\Delta V$ is 1.7/3 m 0.567 V, which is generated with 1/3 of the oscillator peak-to-peak amplitude 1.7 V. The ramp slope $M_e$ is $\Delta V/\tau = 0.567X1000X10^3$. The control IC is CS8424. S is IRF 840 and D is DSE112-06A. 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 $R_e=1Q$, $S_{ni}$

$$= \frac{M_e}{(\frac{1}{2}V_{in}(1/2))} = \frac{1.5}{k_{ni}}$$

and $S_{ni}$ is 1.5$rac{D}{1-D}$. Setting $k_{ni}=0.2$, $S_{ni}=7.5$. For $D=0.6$,

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

$$= \frac{1 - 20.6}{2(1 - 0.6)(7.5X2.8X10^5)} = 4.0$$

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 $k_i = k_{ni}/\tau = 0.2X100X10^3 = 20,000$. 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 $R_{iL}$ 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 \( 216 \times \frac{R_1}{R_2} \) and \( 216 \times \frac{1}{R_2 C_1} \), 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 \( \mu F \). 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 \( k_p = 0.10 \) 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.

References


