Slope 보상을 가진 벅 LED 구동기의 설계 및 실험

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Design and Experiment of Slope-compensated Buck LED Driver

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ABSTRACT

A discrete time domain analysis for the slope-compensated 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]-[8].

In this paper, the systematic discrete time domain approach is adapted to modeling and designing feedback compensator for the slope-compensated 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 I gain k_{ni} is shown in Fig. 1. The eigenvalue λ_1 is dominated by the inductor current state. The transient response of λ_1 after a disturbance is underdamped when k_{ni} is between 0 and 0.49. At $k_{ni} = 0.49$, the system response is critically damped. When k_{ni} is greater than 0.49, 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_2. Using the condition of $(a_{11} + a_{22})^2 - 4(a_{11}a_{22} - a_{12}a_{21}) = 0$, and setting $k_p = 0$, the border equation between the underdamped and overdamped cases can be derived as

$$k_{ni} = \frac{1}{1-2D+2S_{ro}D+\sqrt{(1-2D+2S_{ro}D)^2-(2D^2-2D+1)}} \quad \text{for } k_p = 0 \qquad (1)$$

where $S_{ro} = \frac{LM_e}{V_o R_s}$.

Using (1), I gain curve for the critically damped response is shown in Fig. 2. The system response is overdamped for the integral gain less than the gain curve, and underdamped for the integral gain greater than the curve. For a fixed value of S_{r0}, the optimal integral gain is decreasing with increasing D. Therefore, the optimal integral gain must be determined at the maximum D to avoid underdamped response. Because designing k_{ni} according to the boundary of a lower D results in an oscillatory transient response at D_{max}. Selecting k_{ni} slightly less than or equal to the value on the boundary 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 normalized integral gain k_{ni} slightly less than or equal to 0.45 at D_{max} =0.6 and $S_{ro} = 1.19$ can be chosen for $k_p = 0$. With increasing S_{r0}, the optimal I gain k_{ni} is decreasing, which results in a slower system response.

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. The control IC is CS3842. 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. The output voltage is approximately (3.25V X 5 LEDs in series) 16.25 V.

In the experiment, the ramp peak-to-peak amplitude ΔV is 1.8/4 ≈ 0.45 V, which is generated with $1/4$ of the oscillator peak-to-peak amplitude 1.8 V [9]. The ramp slope M_e is $\Delta V/T_s = 0.45X100X10^3$. For $R_s = 1\ \Omega$, S_{r0} is $\frac{M_e}{(V_o R_s/L)} = \frac{0.45X100X10^3}{16.25X1/430X10^{-6}}$=1.19 and S_r is $\frac{1.19D}{1-D}$. According to the design guideline, $S_{r0} = 1.19$ slightly greater than or equal to 0.9 is selected. For a wide stable range of D, $k_p$is chosen to be 0. From (1), k_{ni} is 0.45 for the maximum D=0.6 and $k_p = 0$. The designed k_{ni} is selected to be 0.4, which is slightly less than 0.45 for D=0.6 and $k_p = 0$. The integral gain is $k_i = k_{ni}/T_s = 0.4X100X10^3 = 40{,}000$.

From the datasheet [27], the Sense of Fig. 7 should be limited within 1 V. The maximum OSC voltage is 2.8 V. If the maximum peak i is set to be 0.8 A, the maximum Sense signal is $\left(\mathrm{OSC}X\frac{1}{4} + R_s i\right)XSF = \left(2.8X\frac{1}{4} + 1X0.8\right)XSF = 1\ V$. So, SF is $2/3$. In Fig. 3, the Sense can be derived as $\mathrm{OSC}\cdot\frac{R_{12}R_{13}}{R_{12}+R_{13}}/(R_{11} + \frac{R_{12}R_{13}}{R_{12}+R_{13}}) + R_s \mathrm{i}\cdot\frac{R_{11}R_{13}}{R_{11}+R_{13}}/(R_{12} + \frac{R_{11}R_{13}}{R_{11}+R_{13}})$. Therefore, $\frac{R_{12}R_{13}}{R_{12}+R_{13}}/(R_{11} + \frac{R_{12}R_{13}}{R_{12}+R_{13}}) = \frac{1}{4}XSF = \frac{1}{6}$ and $\frac{R_{11}R_{13}}{R_{11}+R_{13}}/(R_{12} + \frac{R_{11}R_{13}}{R_{11}+R_{13}}) = \mathrm{SF} = \frac{2}{3}$. Solving these two simultaneous equations gives $R_{11} = R_{13} = 4R_{12}$. The values of $R_{11}, R_{12},$ and R_{13} are chosen to be

48 k, 12 k, and 48 k, respectively. To avoid the loading effect, these resistor values should be much greater than that of the oscillator section resistor of CS3842.

To provide the same dynamic performance, the output feedback gains k_p and k_i should also be multiplied by the scale factor SF in the experimental circuit. For the designed integral gain $k_i' = k_i XSF = 40{,}000X2/3 = 26{,}667$, $R_2' = 6\ k$ and $C_1' = 15\ n$ are chosen. For $k_p = 0$, $R_1' = 0$ is selected.

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 LED currents are measured for start-up transience with increasing integral gain as shown in Fig. 4. As the integral gain increases from 0.14 to 0.4, the eigenvalue λ_2 moves toward the origin, and the transient response of the LED current becomes faster. Because the overall response time is dominated by the location of the slow eigenvalue λ_2. When the integral gain k_{ni} is 0.4, an optimal control response is observed. Increasing the integral gain to 0.9, the system shows an oscillatory underdamped response. The experimental transient responses show a good agreement with the root-locus analysis.

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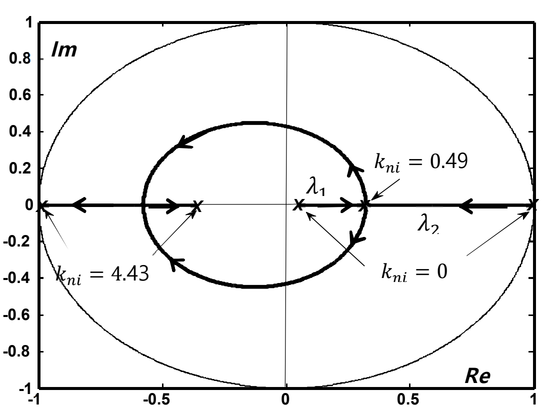


Fig. 1. Root locus as a function of k_{ni}(k_p=0, D=0.4, S_r=0.79)

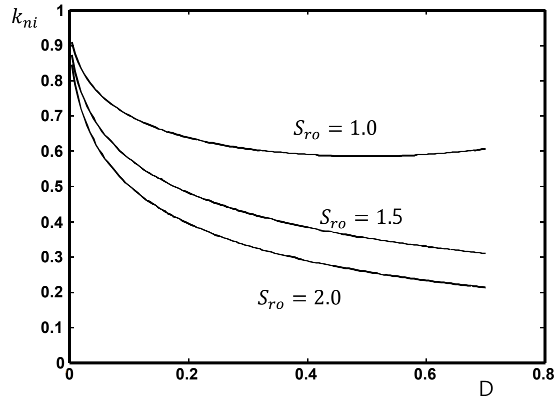


Fig. 2. I gain curve for the critically damped response when $k_p = 0$

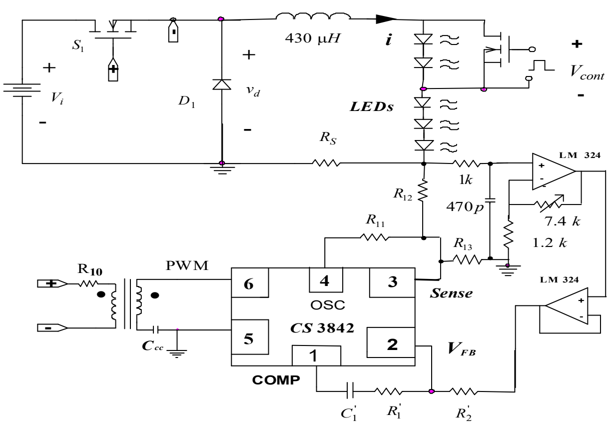
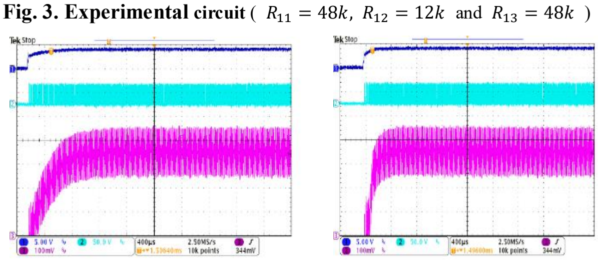
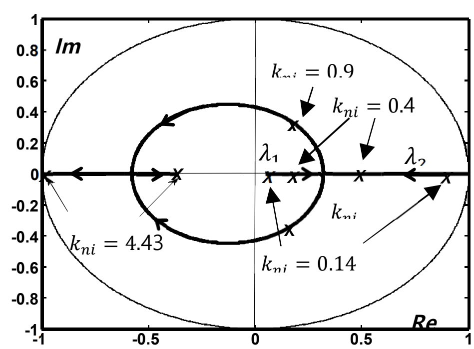


Fig. 3. Experimental circuit ($R_{11} = 48k$, $R_{12} = 12k$ and $R_{13} = 48k$)



(a) k_{ni}=0.14($C_1' = 43\ n$) (b) k_{ni}=0.4($C_1' = 15\ n$)



(c) pole locations related to experimental integral gains.

Fig. 4. Start-up transient responses with increasing integral gain k_{ni} ($V_i = 40\ V$, $V_o \approx 16.25$, $k_p = 0, R_1' = 0, R_2' = 6\ k$). Horizontal scale: 400 $\mu s/div$, vertical scale: top traces-error amplifier output voltage COMP (5 V/div); middle traces - voltage across the freewheeling diode v_d(50 V/div); bottom traces-inductor current i(100 mA/div)