피크전류 제어된 벅 LED 구동기의 모델링 및 제어

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Modeling and Control of Peak Current Controlled (PCC) Buck LED Driver

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ABSTRACT

A discrete time domain modeling and analysis for the peak current controlled (PCC) buck LED driver is presented in this paper. The design guidelines and experimental results for the PCC buck LED driver are presented.

1. Introduction

Small-signal linearized modeling for the current regulated LED driver is of crucial importance in many applications not only for assessing stability and dynamic characteristics but for designing compensators. Numerous attempts have been made to characterize current-mode control system. The average concept is successfully used in the modeling of power converters[1]-[2]. The low-frequency response can be well predicted by the average models. However, one common issue of the average models is that they can't predict subharmonic oscillations in current-mode control. Exact discrete-time model[3] can accurately predict responses. This numerical technique is not useful to be used in practical design. In order to extend the validation of the average models to the high-frequency range, modified average models are proposed based on the results of discrete-time analysis and sampled-data analysis[3]-[5]. 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[6].

In this paper, the systematic discrete time domain approach[7]-[9] is adapted to modeling and designing feedback compensator for the PCC buck LED driver shown in Fig. 1. Root locus analysis is used to derive the stability boundaries and the design guidelines for the PI gains of the feedback compensator, and experimental results are presented to confirm the design.

2. Discrete time domain modeling of PCC buck LED driver

$$\delta X_{k+1} = A \cdot \delta X_k + B \cdot \delta v_r \qquad (1)$$

where

$$\delta X_{k+1} = [\delta i_{k+1}\ \ \delta v_{k+1}]^T, \quad \delta X_k = [\delta i_k\ \ \delta v_k]^T,$$

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \quad B = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix},$$

$$a_{11} = 1 - \frac{1}{(1-D)} \frac{1 + k_p + k_{ni} D}{(1 + k_p + k_{ni} D/2)}, \quad a_{12} = \frac{1}{R_s} \frac{1}{(1-D)} \frac{1}{(1 + k_p + k_{ni} D/2)},$$

$$a_{21} = R_s \frac{k_{ni}^2 D/2}{1 + k_p + k_{ni} D/2}, \quad a_{22} = 1 - \frac{k_{ni}}{1 + k_p + k_{ni} D/2},$$

$$b_1 = \frac{1}{R_s} \frac{1}{(1-D)} \frac{1 + k_p + k_{ni} D}{(1 + k_p + k_{ni} D/2)}, \quad b_2 = -\frac{k_{ni}^2 D/2}{1 + k_p + k_{ni} D/2}, \quad D = V_o / V_i,$$

$$k_p = \frac{R_1}{R_2}, \quad k_{ni} = k_i T_s = \frac{T_s}{R_2 C_1}.$$

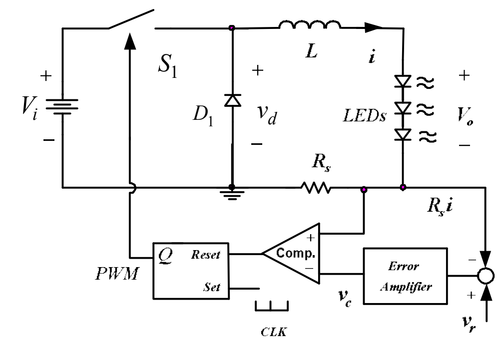


Fig. 1. Peak current controlled buck LED driver with constant-frequency controller.

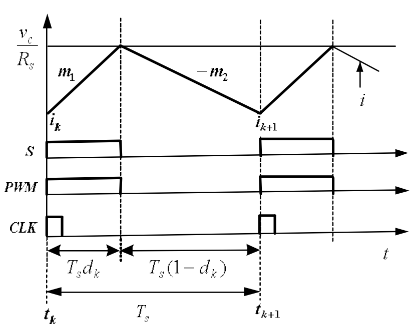


Fig. 2. Key theoretical waveforms of Fig. 1.

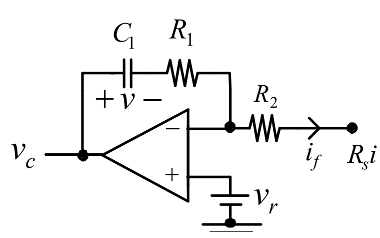


Fig. 3. Proportional-Integral error amplifier circuit.

3. Design Guidelines

Increasing k_{ni} from 0, λ_1 moves towards the unit circle and λ_2 moves towards the origin of the unit circle as shown in Fig. 4. These means the inductor current state becomes slower and the capacitor voltage state of the error amplifier becomes faster. The response time of two states after a disturbance varies inversely with increasing the integral gain. In practical design, it is desirable that the transient response of the inductor current should be faster than that of the error amplifier, which means $|\lambda_1|<|\lambda_2|$. When $|\lambda_1|<|\lambda_2|$, the approximate λ_1 and λ_2 are a_{11} and a_{22}, respectively. From the condition of $a_{11}+a_{22}>0$, the practical range of the normalized integral gain can be derived as

$$0<k_{ni}<\frac{(1-2D)}{(1-D+D^2)}(1+k_p) \quad \text{for } D<0.5 . \qquad (2)$$

Selecting k_{ni} slightly less than the value on the boundary at the maximum D of an operating range, a satisfactory transient response can be achieved.

4. Experimental evaluation

For performance evaluations, a prototype converter has been constructed as shown in Fig. 5. The constant switching frequency is 108 kHz. The normal operationg range of D in the converter is between 0.2 and 0.47. From (2), the design boundary value of k_{ni} for the maximum D = 0.47 and k_p = 0 is 0.08. The designed k_{ni} is selected to be 0.075, which is slightly less than 0.08.

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 integral gain as shown in Fig. 6. As the integral gain increases, the transient response of the LED current becomes faster. Because the overall response time is dominated by the slow error amplifier state. When the integral gain k_{ni} is 0.075, an optimum control response can be obtained. Increasing the integral gain to near the stability boundary, where the error amplifier state is much faster than the current state, the error amplifier is saturated and then come back to a stable operation during the start-up transience.

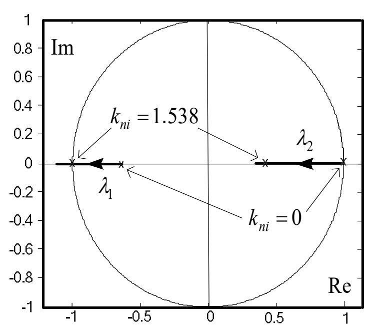


Fig. 4. Root locus in the z-plane when the proportional gain is changed (k_p =1 , D=0.4).

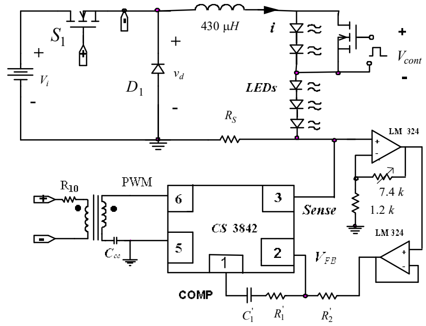
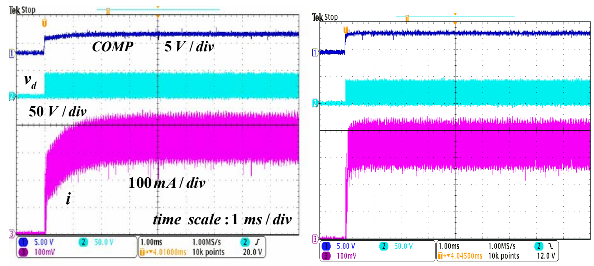


Fig. 5. Experimental circuit.



(a) k_{ni} =0.015 (b) k_{ni} =0.075

Fig. 6. Start-up transient responses with increasing integral gain k_{ni} ($V_i=40V$, $V_o\approx 16.25V$, $k_p=0$)

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