Time-Delay Effects on DC Characteristics of Peak Current Controlled Power LED Drivers

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Abstract

New discrete time domain models for the peak current controlled (PCC) power LED drivers in continuous conduction mode include for the first time the effects of the time delay in the pulse-width-modulator. Realistic amounts of time delay are found to have significant effects on the average output LED current and on the critical inductor value at the boundary between the two conduction modes. Especially, the time delay can provide an accurate LED current for the PCC buck converter with a wide input voltage. The models can also predict the critical inductor value at the mode boundary as functions of the input voltage and the time delay. The overshoot of the peak inductor current due to the time delay results in the increase of the average output current and the reduction of the critical inductor value at the mode boundary in all converters. Experimental results are presented for the PCC buck LED driver with constant-frequency controller.

Key words: Time-delay effect; Peak current control; Power LED drivers; Average output current; PWM DC to DC converters

I. INTRODUCTION

In 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 of up to 100,000 hours. Today, LEDs are available for various colors and they are suitable for white illumination [1].

The luminous flux of LEDs is mostly determined by the LED forward current. Controlling the current accurately is a challenge when each LED has a large manufacturing tolerance in its forward voltage as shown in TABLE I [2]. Furthermore, the forward voltage V_F also varies over temperature with negative temperature coefficient. Therefore, current mode control is needed to achieve constant brightness

of LEDs [3], [4].

Current mode control is a commonly adopted regulation method for pulse-width modulated (PWM) DC to DC converters because of its inherent features such as short-circuit and overload protection, faster response and pulse-by-pulse control. It is commonly believed that for applications with duty cycle $D < 0.5$, the current loop is stable for current mode control without slope compensation. If the required duty cycle is low enough in applications, there is no need for slope compensation, thereby avoiding extra circuitry and as a result, reducing size.

Modeling of current mode controlled converters has been focused on multi-loop regulators with output voltage feedback [5], [6]. In multi-loop regulators, a current controlled power stage inside the conventional output voltage feedback loop constitutes a multi-loop feedback. The outer voltage feedback loop provides the regulated output voltage of converters.

However, LEDs require a stabilized output current. The purpose of this paper is to investigate the   time-delay effects on the average output current and the critical inductor value

at the boundary between the continuous and discontinuous conduction modes in the peak current controlled (PCC) LED drivers without the outer voltage feedback loop.

One new result of the analysis is that the average output current of the PCC buck LED driver is insensitive to input voltage variations when a realistic amount of time delay of 0.4-0.6 μs exists in the control circuit, which is different from the analytical result of the previous works [3], [4], where the time delay is assumed to be zero. On the other hand, the average output current of the PCC boost and buck-boost converters is varied over a wide range with increasing the input voltage. Therefore, the two topologies in the continuous conduction mode are poor for the LED drivers in wide input voltage applications. A second result is that the average output current is affected only by the time delay at turn off and irrelevant to the time delay at turn on in PCC converters. The time-delay effects on the critical inductor value at the boundary between the two conduction modes are investigated too. As the time delay increases, the critical inductor value is reduced in all converters.

TABLE I

EXAMPLE OF LED FORWARD VOLTAGE VARIATIONS

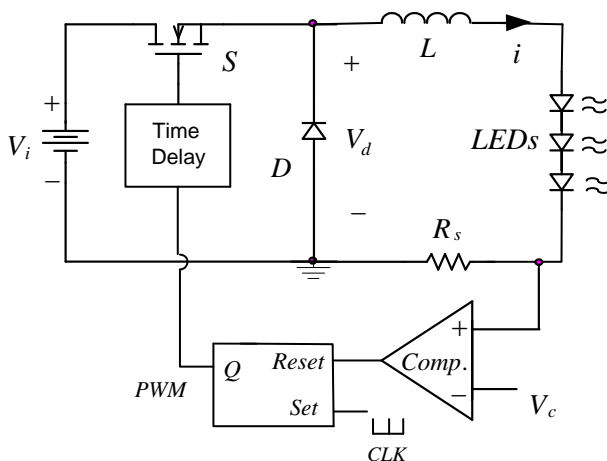| Z-power LED	V_F @ $25^o C$, I_F = 350 mA			V_F deviation
	Min	Typ	Max	
White, Green, Blue	3.0	3.25	4.0	17.2 %
Red	2.0	2.3	3.0	23.4 %

Fig. 1. PCC buck LED driver with constant-frequency controller.

II. DISCRETE TIME DOMAIN MODELING FOR PCC POWER LED DRIVERS

Fig. 1 shows a PCC buck LED driver without slope compensation. Power LEDs require a stabilized output current of 350 mA and more, and have to be supplied by switched mode power supplies to improve the efficiency. By adding a shunt resistor R_s in series to the inductor, the current can be measured via the voltage at the shunt R_s, so that standard circuit topologies and control schemes can be applied. The measured voltage at the shunt R_s has to be very small to avoid additional losses. Thus, both the controller and the shunt resistor have to be connected to common ground.

A. Derivation of the Average Output LED Current for the Continuous Conduction Mode

The clock signal is applied to initiate the switch ON-time uniformly at the switching, or clock, frequency $f_s = 1/T_s$. The switch ON-time is terminated when the inductor current reaches a value proportional to the control signal, where the proportionality factor R_s is the ratio between the voltage presented to the comparator and the current ramp that produces it.

The relationship is determined at the comparator input, whose detailed waveforms are shown in Fig. 2. The control voltage signal is scaled to equivalent current signal by the proportionality factor R_s. One comparator input carries the control current V_c / R_s and the other input carries the inductor current. However, the instantaneous inductor current has a positive ramp of slope $+ m_1$ when the power switch is ON and a negative ramp of slope $- m_2$ when the switch is OFF, and the duty ratio d_k is determined by intersection of the two comparator inputs which, from the geometry of the waveform diagram of Fig. 2(a), is given by

$$i_k + m_1 T_s d_k = \frac{V_c}{R_s} . \qquad (1)$$

This switching control law [7] is termed as the threshold condition [8] or the constraint condition [9].

From the figure, discrete time domain equation for the converter can be represented as

$$i_{k+1} = i_k + m_1 T_s d_k - m_2 T_s (1 - d_k) \qquad (2)$$

If there is a time delay at turn off in the control circuit, the switch does not turn off when the inductor current reaches the control input V_c / R_s, rather it turns off after some time delay. Due to this delay, the inductor current has an overshoot over

V_c / R_s as shown in Fig. 2 (b). Fig. 3 shows the experimental waveforms when control delays are changed. The turn-on delay t_{dn} can not affect the switching control law. The peak inductor current is altered only by the turn-off delay t_{df}. When the control circuit has a time delay at turn off, the switching control law (1) should be modified by

$$i_k + m_1 T_s d_k = \frac{V_c}{R_s} + m_1 t_{df} \qquad (3)$$

where t_{df} is a time delay at turn off. The switching law is irrelevant to the turn-on delay t_{dn} in PCC converters.

In the steady-state, setting $i_{k+1} = i_k = I$, $m_1 = M_1$, $m_2 = M_2$, $d_k = D$, and $t_{df} = T_{df}$, (2) and (3) can be rewritten as

$$M_1 T_s D = M_2 T_s (1 - D)$$

$$I + M_1 T_s D = \frac{V_c}{R_s} + M_1 T_{df} \qquad (4)$$

The steady-state average inductor current is given by

$$I_{avg} = I + \frac{M_1 T_s D}{2} = \frac{V_c}{R_s} + M_1 T_{df} - \frac{M_1 T_s D}{2} \qquad (5)$$

All the above equations apply to any converter. The differences between converters result solely from how the inductor ramps M_1 and M_2 are dependent upon operating conditions.

Buck Converter: During the switch ON-time the inductor is connected between the input and output voltages V_i and V_o, so

$$M_1 = \frac{V_i - V_o}{L} \qquad (6)$$

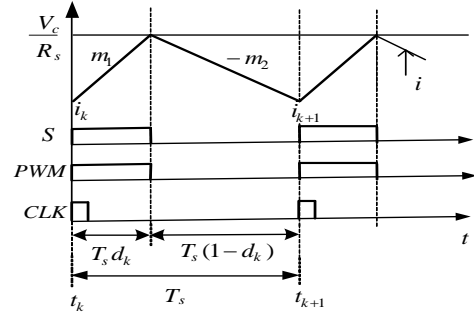During the switch OFF-time the negative slope of the inductor current is given by

$$M_2 = \frac{V_o}{L} \qquad (7)$$

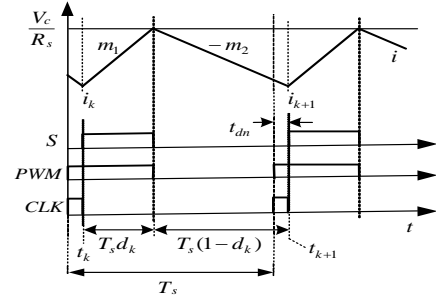Substituting (6) and (7) into (4) and (5) gives the following average output LED current:

$$I_{LED} = I_{avg} = \frac{V_c}{R_s} + \frac{(V_i - V_o)}{L} T_{df} - \frac{V_o (V_i - V_o)}{2 f_s L V_i} . \qquad (8)$$

Boost Converter: During the switch ON-time the inductor is connected across the input voltage V_i, so
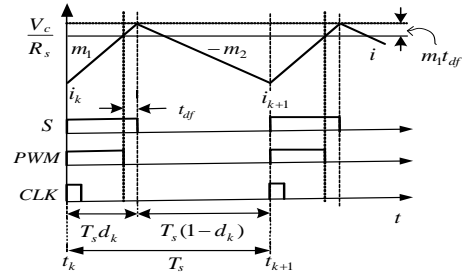
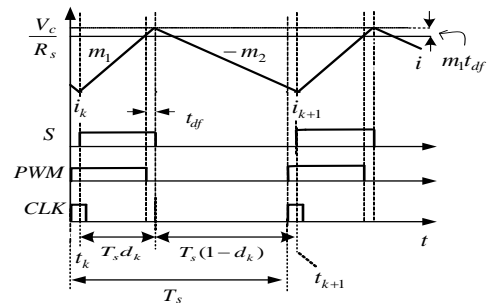$$M_1 = \frac{V_i}{L} . \qquad (9)$$

Without time delay

With turn-on delay t_{dn}

(a) Switching law: $i_k + m_1 T_s d_k = \dfrac{V_c}{R_s}$

With turn-off delay t_{df}

With turn-on and turn-off delays

(b) Switching law: $i_k + m_1 T_s d_k = \dfrac{V_c}{R_s} + m_1 t_{df}$

Fig. 2. Key theoretical waveforms with simple peak current control.

(a) Normal operation.   (b) Large time delay T_{dn}.
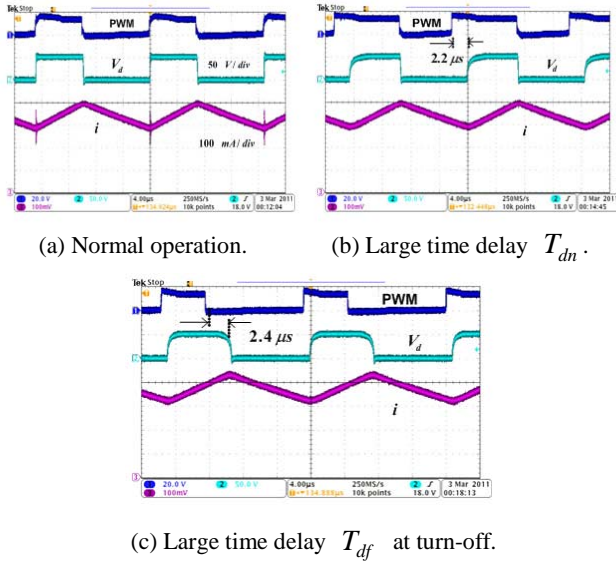

(c) Large time delay T_{df} at turn-off.

Fig. 3. Peak current variations by change of time delay with constant control input.

During the switch OFF-time the negative slope of the inductor current is given by

$$M_2 = \frac{V_o - V_i}{L}. \tag{10}$$

To determine the average output LED current of the boost converter, substituting (9) and (10) into (4) and (5) produces

$$I_{LED} = I_{avg}(1-D)$$

$$= \{\frac{V_c}{R_s} + \frac{V_i}{L}T_{df} - \frac{V_i(V_o - V_i)}{2f_s L V_o}\}(\frac{V_i}{V_o}). \tag{11}$$

Buck-Boost Converter: As for the boost converter,

$$M_1 = \frac{V_i}{L}. \tag{12}$$

During the switch OFF-time,

$$M_2 = \frac{V_o}{L}. \tag{13}$$

As for the boost converter, substituting (12) and (13) into (4) and (5) gives the following average output LED current:

$$I_{LED} = I_{avg}(1-D)$$

$$= \{\frac{V_c}{R_s} + \frac{V_i}{L}T_{df} - \frac{V_i V_o}{2f_s L(V_i + V_o)}\}(\frac{V_i}{V_i + V_o}) \tag{14}$$

B. Determination of the Critical Inductor Value at the Boundary between Two Conduction Modes

The boundary condition between the continuous and discontinuous conduction modes can be determined by setting $I = 0$ in (4) as follows.

$$T_s = (\frac{1}{M_1} + \frac{1}{M_2})(\frac{V_c}{R_s} + M_1 T_{df}). \tag{15}$$

This boundary condition can be converted to $Cuk's$ derivations [10] by using $(V_c / R_s + M_1 T_{df})/2 = V_o / R$ for the buck, and $(V_c / R_s + M_1 T_{df})(1-D)/2 = V_o / R$ for the boost and buck-boost converters. But, $Cuk's$ model cannot be used to investigate the time-delay effect of the control circuit on the DC characteristics. The point of this article is to derive the equations for the critical inductor values as a function of the time delay when the outer voltage feedback is not employed.

Substituting the ON-time and OFF-time slopes into (15) gives the critical value of the inductor L_c at the boundary between the two conduction modes for each converter.

Using (6) and (7), the critical inductor value for the **PCC buck converter** can be derived as

$$L_c = (T_s - \frac{V_i}{V_o}T_{df})\frac{V_o(V_i - V_o)}{V_i}\frac{R_s}{V_c}. \tag{16}$$

Substituting (9)-(10) into (15) gives the critical inductor value for the **PCC boost converter** as the following

$$L_c = (T_s - \frac{V_o}{V_o - V_i}T_{df})\frac{V_i(V_o - V_i)}{V_o}\frac{R_s}{V_c}. \tag{17}$$

Using (12)-(13), the critical inductor value of the **PCC buck-boost converter** can be written as

$$L_c = (T_s - \frac{V_i + V_o}{V_o}T_{df})\frac{V_i V_o}{V_i + V_o}\frac{R_s}{V_c}. \tag{18}$$

When $L > L_c$, all the above converters are in the continuous conduction mode.

III. ANALYSIS OF TIME-DELAY EFFECTS ON DC CHARACTERISTICS

To analyse the time-delay effects on the DC characteristics of the PCC LED drivers in the continuous inductor current mode, the circuit parameters of $f_s = 60\,kHz$ and $L = 1.36\,mH$ are used.

Using (8), Fig. 4 illustrates the time-delay effect on the average output LED current of the PCC buck LED driver with increasing the input voltage. From the previous works [3], the average output LED current drops with the increase of the input voltage, which is true for $T_{df} = 0$. If there is a delay in the control circuit, the switch does not turn off when the inductor current reaches the control input V_c / R_s, rather it turns off after some time delay. Due to this delay, the inductor current has an overshoot of $M_1 T_{df}$ over V_c / R_s.

This current overshoot compensates for the reduction of the average output current due to the increase of the input voltage. Therefore, the simple peak current control can provide a good current accuracy for the buck LED driver over wide input voltage variations when a proper time delay of approximately 0.4-0.6 μs exists in the control circuit. This is a realistic amount of time delay in the control circuit.

The graph of (11) is shown in Fig. 5(a) for $V_o = 55\,V, V_c / R_s = 540\,mA$. The average output LED current varies over a wide range with increasing the input voltage. Therefore, the PCC boost LED driver can not be used for the wide input voltage applications.

Using (14), Fig. 5(b) shows the average output LED current of the PCC buck-boost LED driver for $V_o = 15\,V, V_c / R_s = 550\,mA$. The output LED current varies significantly with increasing the input voltage. Thus, the PCC buck-boost LED driver is poor for wide input voltage applications.

As T_{df} increases, the average output LED current increases in all of the basic converters. From Figs. 4-5, it can be said that the PCC buck converter is most suitable for the power LED driver, especially in wide input voltage applications.

Using (16)-(18), the time-delay effects on the critical inductor value curve at the boundary between the two conduction modes are shown in Figs. 6-7. As the time delay increases, the critical inductor value is reduced in all converters.

Due to the time delay T_{df} , the peak inductor current has an overshoot of $M_1 T_{df}$ over the control input of V_c / R_s , which means the control input of $V_c / R_s + M_1 T_{df}$ when the time delay is zero. This overshoot of the peak inductor current results in the increase of the average output current and the reduction of the critical inductor value at the boundary between two conduction modes in the PCC PWM converters.
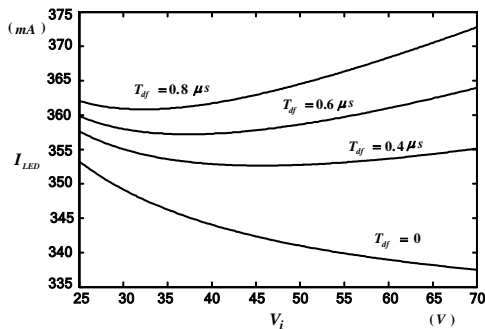

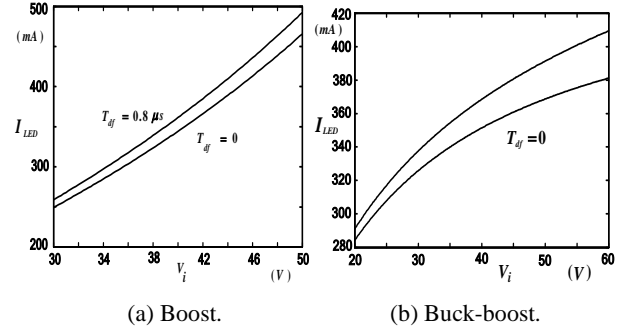(a) Boost.   (b) Buck-boost.

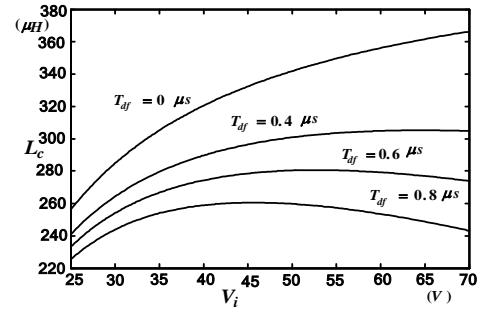Fig. 5. Time-delay effect on the average output LED current of the PCC boost and buck-boost LED drivers.

Fig. 6. Time-delay effect on the critical inductor value curve for the PCC buck converter ($V_o = 10\,V, V_c / R_s = 390\,mA$).

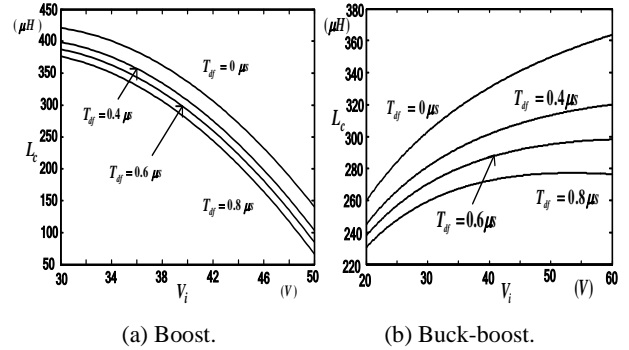(a) Boost.   (b) Buck-boost.

Fig. 7. Time-delay effect on the critical inductor value curve for the PCC boost and buck-boost converters.

IV. EXPERIMENTAL EVALUATION

For performance evaluations, a prototype converter has been constructed as shown in Fig. 8. The constant switching frequency is 58.8 kHz. The control IC is CS3842, where no compensation slope is used. The peak control input V_c / R_s is 390 mA. 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 .

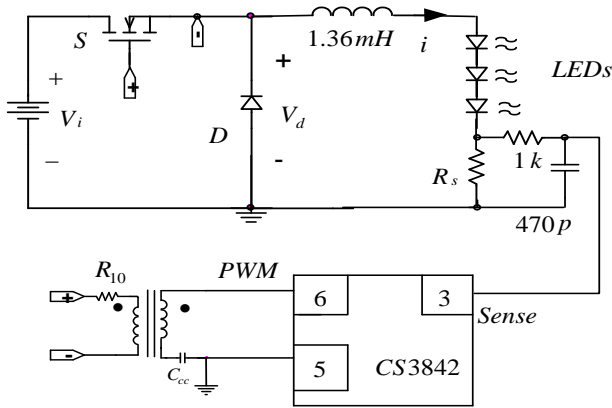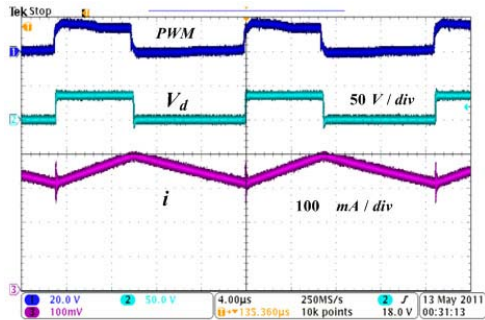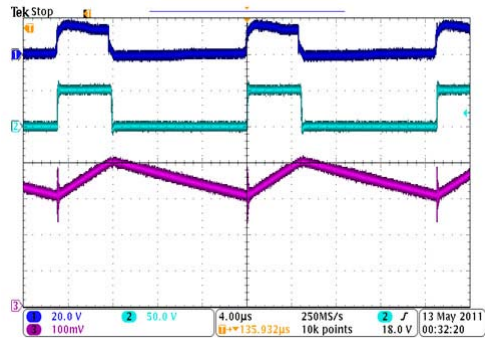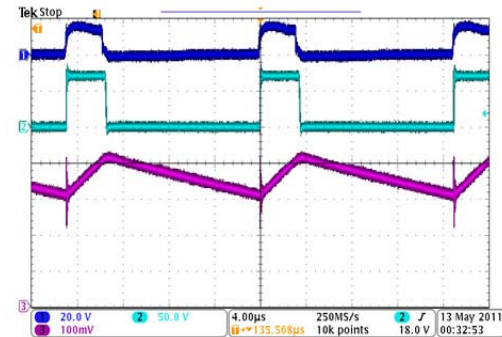This LED forward voltage varies from 2.9V to 3.8V, for a nominal of 3.25 V [2].

Fig. 4. Time-delay effect on the average output LED current of the PCC buck LED driver ($V_o = 10\,V, V_c / R_s = 390\,mA$).

Fig. 8. Experimental PCC buck LED driver ($f_s = 58.8\,kHz$, $V_c / R_s = 390\,mA$).

(a) $V_i = 35V$.

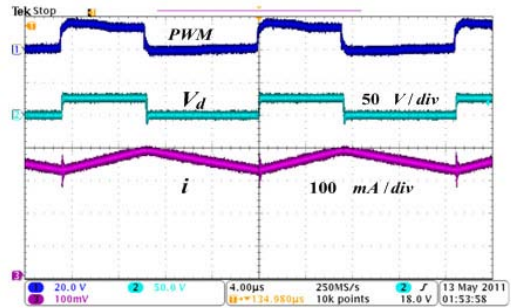
(b) $V_i = 50V$.
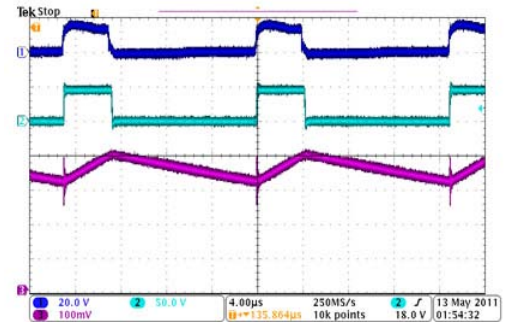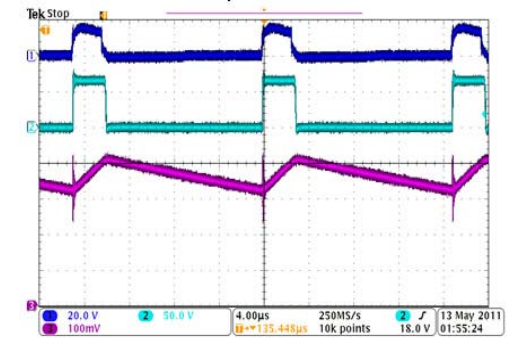

(c) $V_i = 70V$.

Fig. 9. LED current waveforms with increasing the input voltage ($V_o \approx 13V$, $V_c / R_s = 390\,mA$).

(a) $V_i = 25V$.


(b) $V_i = 45V$.

(c) $V_i = 65V$.

Fig. 10. LED current waveforms with increasing the input voltage when the output voltage is varied ($V_o \approx 9.75V$, $V_c / R_s = 390\,mA$).

With four LEDs connected in series, which provides a typical loading voltage of approximately (3.25V X 4 LEDs in series) 13 V, the measured LED currents are shown in Fig. 9. As the input voltage increases, the average LED current doesn't decrease in this figure due to the time delay in the control circuit. This experimental result is different from the previous analytical result obtained from assuming $T_{df} = 0$.

Due to the time delay in the control circuit, the average LED current is insensitive to the input voltage variations in the PCC buck converter. Fig. 10 shows the measured LED current waveforms at a typical output voltage of approximately (3.25V X 3 LEDs in series) 9.75V, which means the output voltage variation of about 25 % compared to the output voltage of 13 V in Fig. 9. This experimental result shows that the average LED current of the PCC buck
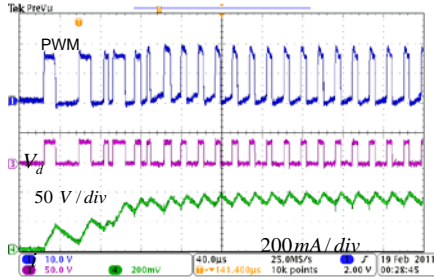
(a) $V_i = 35V$.
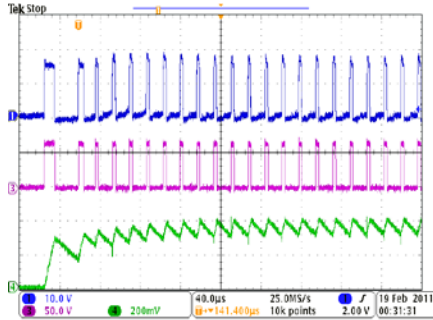
(b) $V_i = 65V$.

Fig. 11. Start-up transient responses of Fig. 8.
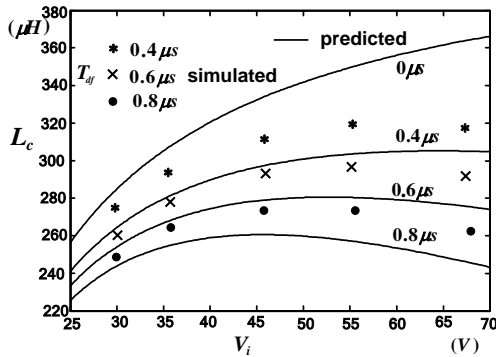($V_o \approx 13\,V$, $V_c / R_s = 390\,mA$).

Fig. 12. Simulated critical inductor values for the PCC buck converter ($V_o = 10\,V$, $V_c / R_s = 390\,mA$).

converter doesn't vary significantly due to the change of the LED forward voltage. From Figs. 9-10, it can be said that the PCC buck converter is excellent for the LED drivers in wide input voltage applications.

The start-up transient responses are shown in Fig. 11. The LED current is well limited below the peak current as expected. Fig. 12 shows the simulated critical inductor values of the PCC buck converter at the boundary between the two conduction modes, the simulated data are obtained from PSPICE simulation. The small discrepancy between the predicted and the simulated critical inductor values is mainly due to both the forward voltage of the freewheeling diode D

and the conduction voltage of the active switch S.

V. CONCLUSION

This proposed discrete time domain modeling describes for the first time the effects of control delay on the average output current and the critical inductor value at the boundary between the two conduction modes in the PCC power LED drivers. The total time delay is the sum of all the propagation delays from the PWM comparator to the power switch. Due to this delay, the inductor current has an overshoot over the peak current control input. This overshoot of the peak inductor current results in the increase of the average output current and the reduction of the critical inductor value at the boundary between the two conduction modes in all converters.

When the input voltage varies, the average output LED current of the boost and buck-boost LED drivers operating in continuous conduction mode with the simple peak current controller, varies over a wide range. These two topologies are not suitable for the power LED drivers in wide input voltage applications. On the other hand, the PCC buck LED driver maintains the average output LED current relatively at a constant level with increasing the input voltage when a realistic amount of time delay exists in the control circuit. Because the current overshoot by the time delay compensates for the average output current reduction from increasing the input voltage in the PCC buck converter. Thus the PCC buck converter operating in the continuous conduction mode is most suitable for the power LED driver, especially in wide input voltage applications.

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