An ACHT With EAOT Constant Current Control Method in LED Lighting

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Abstract: A control method named average current-detection and hysteresis turn-off (ACHT) with enhanced adaptive off-time (EAOT) in non-isolated buck LED driver is proposed in this paper to achieve accurate constant current. The proposed control method is implemented by the ACHT loop which is utilized to control on-time and the EAOT loop which is utilized to generate an adaptive off-time (AOT). Five conventional control methods are thoroughly analyzed and compared. Analysis and results prove that the proposed ACHT with EAOT can detect valley current based on low-side sensing method, work stably, output average current with high precision, and avoid the current spike without introducing leading-edge blanking (LEB). The design was implemented with TSMC' 1μm 700V BCD process.

1. Introduction

The light-emitting-diode (LED) has become the mainstream of today's lighting sources due to its wide color gamut, dimming capability, energy saving and long lifetime [1, 2]. Because the brightness of LED is decided by the average current through it. Small voltage fluctuations of LED's forward voltage drop will cause large fluctuations of current through it and thus influence the brightness of LED. Therefore, constant current drive is commonly used to drive LED rather than constant voltage drive [3].

In recent years, some constant current control techniques based on LED driver have been proposed to achieve strict constant current. The peak current control (PCC) with constant off-time (COT) causes an uncertainty between peak current and average current because it cannot control valley current. The PCC with COT has been theoretically proved difficult to achieve constant current [4]. To control valley current, the hysteretic current control (HCC) with low side sensing method [5] and the HCC with high side sensing method [6, 7] are developed. These control methods managed to sense valley current. However, detecting valley current without complicated circuitry and the influence of the current spike when the power switch (SW) turns on has not been well solved yet.

The pulse-level-modulation (PLM) [8] with constant frequency (CF) can obtain approximate constant current by adopting calculating the error between inductor current's integral and pre-defined average current's integral during on-time. In the HCC with adaptive off-time (AOT) [9], error of integrals of on-time current and pre-defined average current is utilized to generate AOT to work steadily. However, there are problems existing in both the PLM with CF and the HCC with AOT, which will be revealed and analyzed in depth in this paper.

To solve above issues, based on non-isolated buck LED driver, a control method named as average current-detection and hysteresis turn-off (ACHT) with enhanced adaptive off-time (EAOT) is proposed to achieve accurate constant current. During on-time, the time from valley current Iv to target average current Ia0 equals to the time from Ia0 to peak current Ip. In the time period from Ia0 to Ip, the error between inductor current IL and reference current Im is integrated as error feedback information. This error feedback information is used to generate an AOT. The ACHT with EAOT can detect Iv based on low side sensing method, work stably, and output average current with high precision. Meanwhile, it avoids the current spike without introducing leading-edge blanking (LEB).

2. Architecture of proposed control scheme

The architectural block diagram of the ACHT with EAOT control method is shown in Fig. 1. The proposed circuit is the dashed box, which is composed of the ACHT loop and the EAOT loop. The ACHT loop is utilized to control on-time and the EAOT loop is used to generate an AOT.

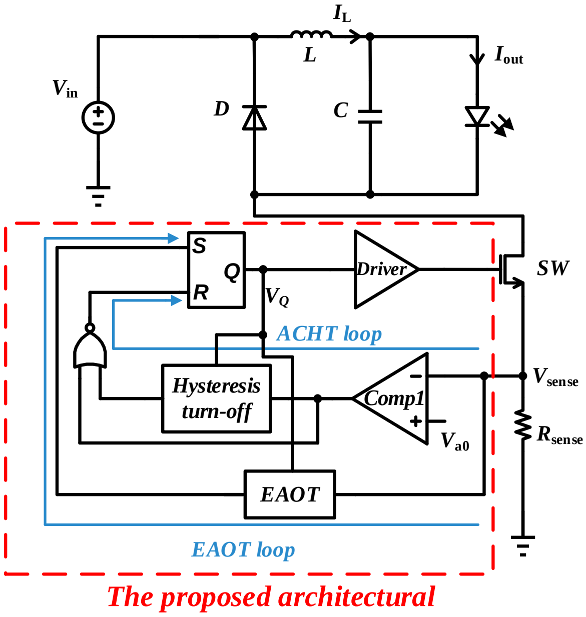


Figure 1. Architectural block diagram of the ACHT with EAOT control method which is composed of the ACHT loop and the EAOT loop.

2.1 ACHT Loop

The key modules of the ACHT loop are the comparator Comp1 and the Hysteresis turn-off. As shown in Fig. 2(a), the Hysteresis turn-off consists of two current mirrors, three switches (i.e., SW1, SW2, and SW3), the capacitor C_H, as well as the comparator Comp2.

During on-time, the interval between valley current I_v and target average current I_{a0} is t_1, the interval between target average current I_{a0} and peak current I_p is t_2, and the SW1 is on. During the t_1 of on-time, the output of Comp1 is at high level, the SW2 is on so the C_H is charged. During the t_2 of on-time, the output of Comp1 flips into low level, the SW3 is on so the C_H is discharged. Because the charge current and the discharge current are same, (1) can be realized as follows,

$$t_1 = t_2 \tag{1}$$

In continuous conduction mode (CCM), (1) makes (2) hold. (2) means that I_v and I_p are symmetric about I_{a0}.

$$I_p - I_{a0} = I_{a0} - I_v \tag{2}$$

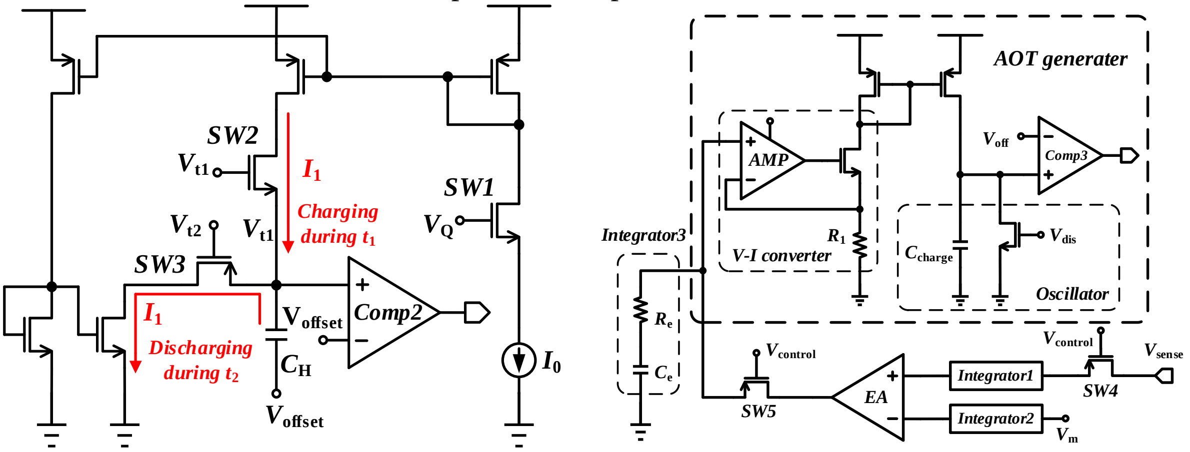
The formula (3) is derived by (2).

$$I_v = 2I_{a0} - I_p \tag{3}$$

Because I_p can be sensed directly through the low side current sensing resistor R_{sense}, *iv* is able to be detected without complicated circuitry as (3) indicates.

2.2 EAOT Loop

Fig. 2(b) depicts the implementation of the EAOT. The EAOT loop mainly contains five components: the Integrator1, the Integrator2, the Integrator3, the error amplifier EA, and the AOT generator. The AOT generator is composed of the V-I converter, the current mirror, the capacitor-based oscillator, and the comparator Comp3.



(a) (b)

Figure 2. (a) The Hysteresis turn-off is implemented by charging CH during t1 and discharging CH during t2 with the same current. (b) In the EAOT, error feedback information is generated through Integrator1, Intergrator2, EA, and Integrator3. AOT generator utilizes this error feedback information to adjust off-time.

During the t_2 of on-time, the SW4 and the SW5 are on. Through Integrator1, Integrator2 and EA, the error η between integral of I_L and integral of I_m is calculated, as shown by (4), where nT is the n^{th} period, $n \in$ N.

$$\eta = \int_{nT+t_1}^{nT+t_1+t_2} (I_L - I_m)dt. \quad (4)$$

$$I_m = \frac{I_{a0} + I_{p0}}{2} \quad (5)$$

Im is defined by (5), where Ip0 is the target peak current. The voltage across Ce is defined as Ve. At the beginning of t2, IL is smaller than Im, η decreases thus the EA sinks current from Integrator3, so Ve decreases. And when IL is greater than Im, η increases thus the EA sources current into Integrator3, so Ve increases. So, the error η is transformed into Ve by the Intergrator3. Ve is the error feedback information which is used to adjust off-time.

During off-time, the SW4 and the SW5 are off, the control signal of the amplifier AMP flips into high level. Both the V-I converter and the current mirror convert V_e into charge current of the capacitor C_{charge}. The C_{charge} is charged from zero to the reference voltage of the Comp3 V_{off}, so the Comp3 flips into high level, then the SW turns on. The length of off-time is determined by the duration of the charging time of C_{charge}.

When V_e is higher, the charging current is greater, so the off-time is shorter. When V_e is lower, the charging current is smaller, so the off-time is longer.

3. Analysis of Average Current and Stability

In this chapter, the principle of outputting constant current of ACHT with EAOT is discussed in detail and then six control schemes include conventional and proposed control methods are discussed and compared.

3.1 The Principle of Outputting Constant Current

When the system works at steady state, *iv* is equal to target valley current I_{v0} and I_p is equal to I_{p0}. Because $I_{a0}=(I_{v0}+I_{p0})/2$, average current I_a is equal to I_{a0}. η is equal to zero, the sink current and the source current of the EA are equal and V_e keeps at a certain value V_{e_ideal}, the off-time t_{off} is a certain value t_{off0}. As shown in Fig. 3, i is the disturbance occurs at zero moment. One assumption is the amplitude of i is much smaller than I_v, another assumption is that the system can work near the steady state and the rising slope of I_L and the falling slope of I_L remain unchanged after adding a small disturbance.

If i is positive, *iv* is greater than I_{v0} and I_p is smaller than I_{p0}, by (4), η is negative thus the sink current is greater than the source current, so V_e of this period is smaller than V_e of previous period, thus t_{off} of this period is longer than t_{off} of previous period, i.e., AOT generator lengthens the off-time to make the disturbance of next period approach zero.

If i is negative, *iv* is smaller than I_{v0} and I_p is greater than I_{p0}, by (4), η is positive thus the sink current is smaller than the source current, so V_e of this period is greater than V_e of previous period, thus t_{off} of this period is shorter than t_{off} of previous period, i.e., AOT generator shortens the off-time to make the disturbance of next period approach zero.

As a result, the system can return to the state of stable and output constant current I_{a0} due to the adjustment of t_{off} as shown in Table 1.

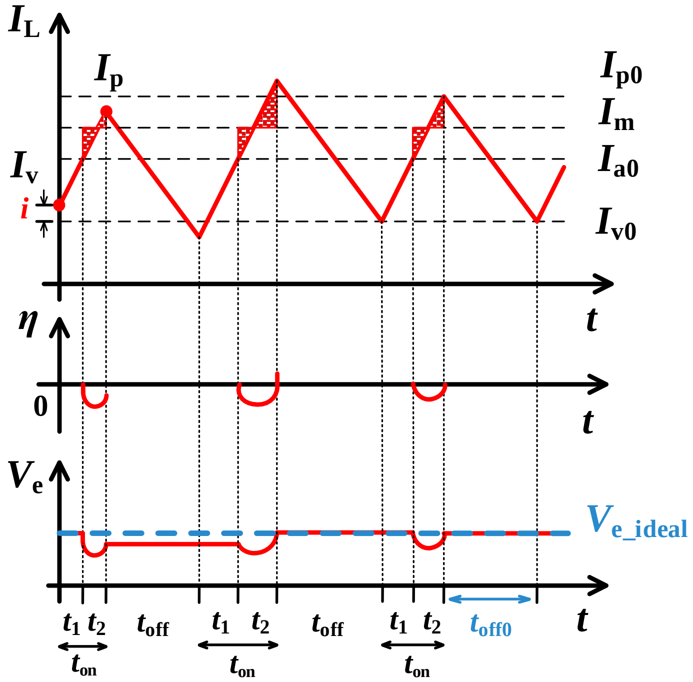


Figure 3. Disturbance i occurs at zero moment, η and Ve are varied with the disturbance, thus toff which depends on Ve is changeable, hence the ACHT with EAOT can return to stable state and output constant current Ia0.

Table 1. State of the System after Disturbance Occurs.

Disturbance	**State of the system**				
$i>0$	$I_v>I_{v0}$	$I_p<I_{p0}$	$\eta<0$	V_e decreases	t_{off} increases
$i<0$	$I_v<I_{v0}$	$I_p>I_{p0}$	$\eta>0$	V_e increases	t_{off} decreases
$i=0$	$I_v=I_{v0}$	$I_p=I_{p0}$	$\eta=0$	V_e keeps constant	t_{off} keeps constant

3.2 Analysis of Traditional Control Methods

The average current expressions, correlation with peripheral circuits, and stability of six different operating modes are analyzed and shown in Table 2.

The expression of disturbance after *n* periods of the PCC with COT is zero. Nevertheless, the average current expression of the PCC with COT is not a constant value due to the influence of peripheral circuits parameters.

The expression of disturbance after *n* periods of the PLM with CF approximately equals $(-2)^n i$ which is divergent. It proves that this control method cannot back to the state of equilibrium after disturbance. Thus, the expression of average current after disturbance is not a constant value. Furthermore, there is an error exists in the integral of rising inductor current due to the current spike. Consequently, the PLM with CF cannot output constant current.

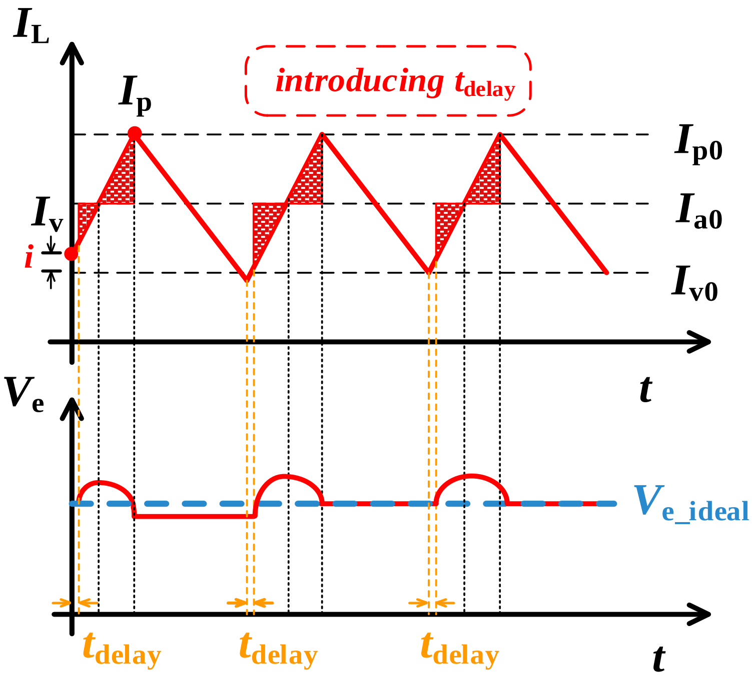


Figure 4. The average current of the HCC with AOT is not constant due to introducing tdelay even though this control method can keep stable.

Because the HCC with AOT has introduced AOT, the disturbance after *n* periods of this control method equals zero which proves that it can remain stable. However, the HCC with AOT cannot output constant current, because it has introduced LEB, then pre-defined delay time brings an error to the expression of average current which associates with V_{in}, V_{out} and L. As shows in Fig. 4.

When applying the ACHT with traditional control schemes, as shown in Table 2, the expression of disturbance after *n* periods of the ACHT with COT equals $(-1)^{ni}$ which indicates that it cannot maintain stable. Moreover, the ACHT with COT cannot achieve constant current because the expression of average current after disturbance is not a constant value.

Because the expression of disturbance after *n* periods is convergent, the ACHT with COT and slope compensation can back to steady state. Whereas, the expression of average current is not constant, because it correlates with peripheral circuits parameters as well due to introducing slope compensation.

3.3 Analysis of the ACHT with EAOT

The expression of disturbance after *n* periods of the ACHT with EAOT is zero and the expression of average current of this control method is a constant value I_{a0}. The integral of I_L is carried out during t_2 in the ACHT with EAOT which means that it succeeds in avoiding the current spike when the SW turns on without introducing LEB.

Table 2. Average Current Expressions, Correlation with Peripheral Circuits, and Stability of Different Operating Modes.

Control method	**Average current**	**Independent of**			**Disturbance after *n* periods if disturbance *i* occurs at zero moment**	**Convergence**
		V_{in}	V_{out}	L		
PCC+COT	$I_{p0}-\frac{V_{out}T_{off}}{2L}$ [abc]	Y[h]	N[i]	N	0	convergent
PLM+CF	$\frac{1}{T}\left\{\frac{2I_{a0}(I_{p\_ad}-I_{a0})L}{V_{in}-V_{out}}+I_p\left[T-\frac{2(I_{p\_ad}-I_{a0})L}{V_{in}-V_{out}}\right]-\frac{V_{out}}{2L}\left[T-\frac{2(I_{p\_ad}-I_{a0})L}{V_{in}-V_{out}}\right]^2\right\}$ [de]	N	N	N	$(-1-2\frac{V_{out}}{V_{in}-V_{out}})^n i$	divergent
HCC+AOT	$I_{a0}-\frac{(V_{in}-V_{out})t_{delay}}{2L}$ [f]	N	N	N	0	convergent
ACHT+COT	$\frac{4I_{a0}(I_{p\_ad}-I_{a0})L^2+(2I_{p\_ad}L-V_{out}T_{off})(V_{in}-V_{out})T_{off}}{4(I_{p\_ad}-I_{a0})L^2+2(V_{in}-V_{out})T_{off}L}$	N	N	N	$(-1)^n i$	divergent
ACHT+COT + slope compensation	$I_{a0}-\frac{m_a\left(I_{p\_steady}-I_{a0}\right)L}{V_{in}-V_{out}}$ [g]	N	N	N	$(-\frac{V_{in}-V_{out}-m_aL}{V_{in}-V_{out}+m_aL})^n i$	convergent
ACHT+EAOT	I_{a0}	Y	Y	Y	0	convergent

a. V_{out} is the output voltage.
b. T_{off} is the COT.
c. L is the inductor.
d. T is the time period of PLM with CF.
e. V_{in} is the input voltage.
f. t_{delay} is the pre-defined delay time HCC with AOT has used.
g. $-m_a$ is the slope of slope compensation.
h. Y means yes.
i. N means no

The proposed ACHT with EAOT control method was implemented with TSMC' 1μm 700V BCD process. I_{a0} and I_{p0} are set as 43.9mA and 56.3mA, respectively. According to (5), I_m equals to 50.1mA.

As Fig. 5 shows the simulation results of waveforms of inductor current I_L and error information voltage V_e. I_p equals to 56.45mA and I_v equals to 31.78mA. Output average current I_a can be calculated as 44.12mA. The error between I_{a0} and I_a is about 0.5%, which indicates that the proposed control method can output average current precisely. t_{off0} of every period is 11.49μs and V_{e_ideal} is 3.84V.

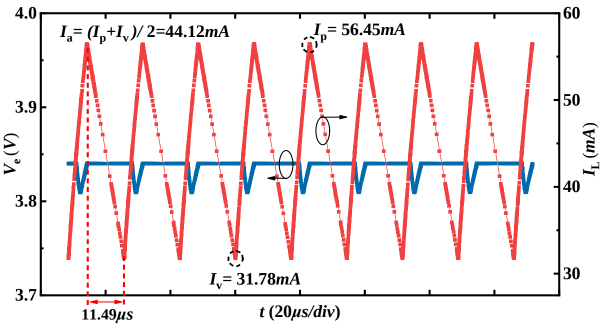


Figure 5. Waveform of inductor current IL and error information voltage Ve of ACHT with EAOT using HSpice simulation.

4. Conclusion

A novel control method named ACHT with EAOT in non-isolated buck LED driver is proposed in this paper. The control method is implemented by the ACHT loop which is utilized to control on-time and the EAOT loop which is used to generate an AOT. Valley current detection based on low side sensing method can be realized in this design. Five conventional control schemes are analyzed in depth and proved that they cannot achieve constant current. The PLM with CF and the ACHT with COT cannot remain stable after disturbance therefore they cannot realize constant current control. The PCC with COT, the HCC with AOT, and the ACHT with COT and slope compensation can return to the stable state after disturbance but they cannot realize constant current control as well. Nevertheless, the results show that the ACHT with EAOT can remain stable and achieve accurate constant current independent with the peripheral circuit parameters. Meanwhile, the proposed method can avoid the current spike without introducing LEB.

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