Hysteretic Controlled Buck Converter With Switching Frequency Insensitive to Input/Output Voltage Ratio

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Abstract- This paper proposes a hysteretic control buck converter with constant switching frequency. There even when the input/output voltage ratio in the steady changes, the switching frequency does not change (only on-time changes). On the other hand, when the load changes in the transient state, the switching frequency changes for quick response. We have designed and simulated the proposed circuit, and confirmed its operation.

Keywords: DC-DC Converter, Hysteric Control, Constant On Time, Switching Frequency

1. Introduction

Recently, most electronic appliances use many switching converters, and the efforts of their realization with high efficiency, fast response, small size and lightweight at low cost are being continued. Especially in CPUs/MPUs very quick changing from the standby to the operating states is required, and there the hysteretic controlled converters are often used because of their high speed response.

However their switching frequency is changed by its variations of their electric parts. In order to keep the switching frequency stable, the constant-on-time (COT) control method is usually used. Furthermore in order to reduce the output voltage ripple, the ceramic capacitors with small equivalent series resister (ESR) are able to utilize due to the ripple injection method. However, with these methods, the switching frequency is changed by the input/output voltage ratio which adversely affects the control characteristics.

For this reason, we investigate to make the switching frequency constant by varying the COT pulse width according to the input/output voltage ratio.

2. Constant-On-Time Control Method

Fig. 1 shows the buck converter circuit with the COT control and Fig. 2 shows its waveforms. When the PWM pulse is changed from H to L at t_0, the switch SW is turned off and the inductor current i_L starts to decrease. Then V_r in Fig. 1 becomes lower than the reference voltage V_{ref} and the PWM signal turns H. Next, SW is turned on and i_L is increased at t_1. Furthermore, V_r also starts to increase and PWM is changed to L after the constant on-time has elapsed.

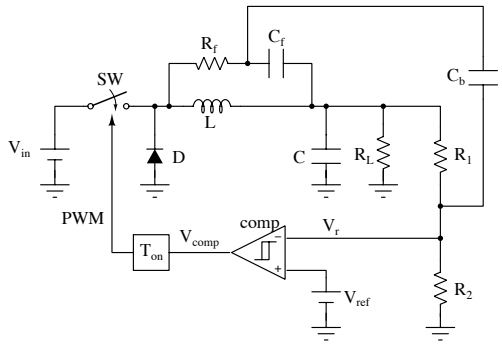

Fig. 1. Buck converter with COT control.

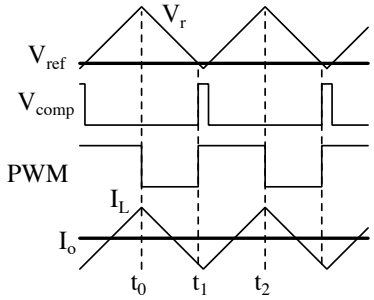

Fig. 2. Waveforms during COT operation.

3. Constant Switching Frequency

3.1 Circuit and Operation

The duty ratio D in a steady state and the period T_s of the PWM signal in the buck converter are shown as follows:

$$D = \frac{T_{on}}{T_s} = \frac{V_o}{V_{in}} \qquad \cdots (1)$$

$$T_s = \frac{V_{in}}{V_o} T_{on} \qquad \cdots (2)$$

In eq. (2), T_s is changed by V_{in} or V_o because the COT pulse width T_{on} keeps constant. It is the good solution to change T_{on} in response to changes of V_{in} or V_o. Fig. 3 shows the proposed T_{on} pulse generator. In Fig. 3, the collector current i_c is obtained by eq. (3), and the voltage of the saw-tooth (SAW) signal is represented by eq. (4).

$$i_c = \frac{R_1}{R_e(R_1 + R_2)} V_{in} \qquad \cdots (3)$$

$$V_{SAW}(t) = \frac{1}{C_c} \int i_c dt = \frac{1}{C_c} \frac{R_2}{R_e(R_1 + R_2)} V_{in} t \qquad \cdots (4)$$

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Since it switches H/L of PWM when the voltages of V_+ (which is divided from V_o) and SAW match, the time t_p is given by eq. (5).

$$t_p = \frac{R_{o2}}{R_{o1}+R_{o2}} \frac{C_c R_e (R_1+R_2)}{R_1} \frac{V_o}{V_{in}} = k\frac{V_o}{V_{in}} \quad \cdots (5)$$

From this equation, t_p is proportional to V_o and inversely proportional to V_{in}. Fig. 4 shows the affect of V_{in} and V_o changes to PWM.

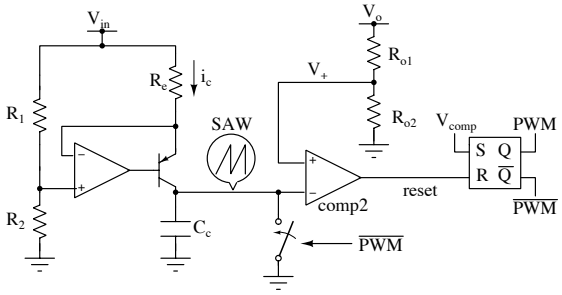


Fig. 3. Proposed T_{on} pulse generator

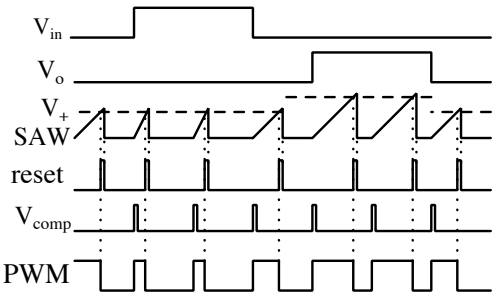


Fig. 4. PWM in response to the input/output voltage change

3.2 Simulation Result

Fig. 5 shows the simulated output voltage for the load change with parameters in Table1, where SIMPLIS is used as a simulator. The switching frequency is 640kHz and the output voltage ripple in steady state is sufficiently small at $5mV_{pp}$ when I_o is 1A. When I_o is changed from 1A to 2A, the under-shoot voltage is 18mV and the over-shoot is 23mV. The rise time t_r is 2.2us which is the duration from load change time to peak time of the under-shoot and dead time is not taken into account there.

Table 1. Parameters in the proposed circuit

V_{in}	12V	C_f	270pF
V_o	5.0 V	R_f	470kΩ
L	4.7uH	C_1	470pF
C_o	100uF	R_1	4kΩ
R_c	2mΩ	R_2	1kΩ

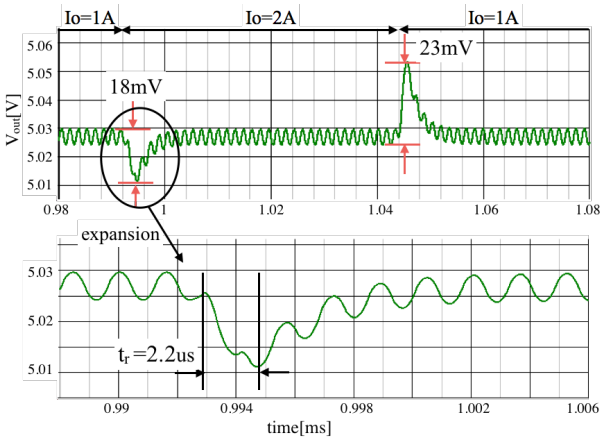


Fig. 5. Simulated output voltage for the load change

3.3 Switching Frequencies for Input/Output Voltage Change

Figs. 6 and 7 show the switching frequencies for the input/output voltage changes in the conventional and proposed methods. In Fig. 6, the switching frequency changes by 58% with the conventional method, whereas it changes only by 6% with the proposed method from V_{in} change from 10V to 24V at V_o=5V. Also, in Fig. 7, the switching frequency changes by 66% on the conventional, however it changes only by 2% with the proposed for V_o change from 2V to 6V at V_{in}=10V. On the other hand, against the change of the output current, the switching frequency is almost constant in both methods as shown in Fig. 8.

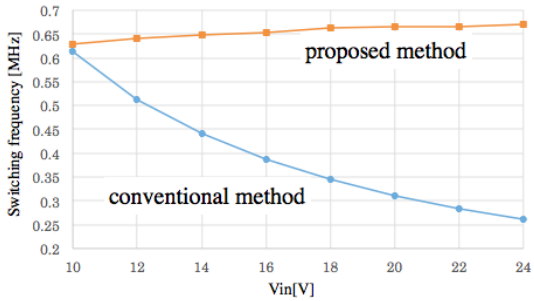


Fig. 6. Switching frequency and input voltage

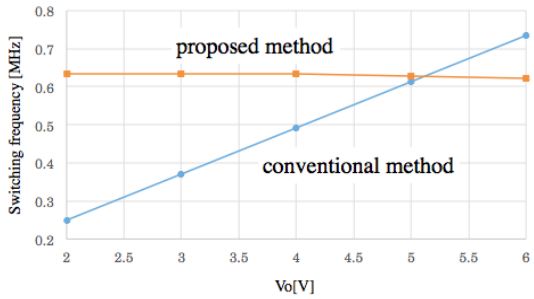


Fig. 7. Switching frequency and output voltage

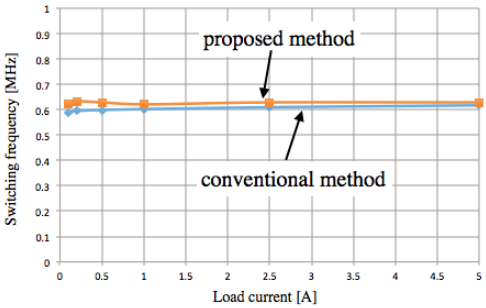


Fig. 8. Switching frequency for output current change.

4. Transfer Characteristics of Proposed Circuit

Fig. 9 shows a block diagram of the proposed circuit. $G_{dv}(s)$ represents the power stage transfer characteristic from ΔD to ΔV_o, $H_{comp}(s)$ does transfer characteristic from ΔV_o to ΔD, and $H_d(s)$ shows dead time by constant on-time pulse. Overall loop transfer function G(s) is given by as follows [1]

$$G(s) = G_{dv}(s) \cdot H_{comp}(s) \cdot H_d(s)$$
$$= \frac{V_{in}(1+sr_cC_o)}{1+2\delta\frac{s}{\omega_0}+(\frac{s}{\omega_0})^2} \cdot \frac{R_f}{V_{in}Z_1}(1+sZ_1C_f) \cdot e^{-sDT_{on}} \cdots (6)$$

Here,

$$\omega_0 = \sqrt{\frac{1+r_L/R}{LC_o}} \cdots (7)$$

$$\delta = \frac{\sqrt{L/C_o}+R(r_L+r_c)\sqrt{C_o/L}}{2R\sqrt{1+r_L/R}} \cdots (8)$$

Fig. 10 shows the Bode plot of eq. (6), which presents the differences against the variance of V_{in} or V_o. At the crossover frequency of 100kHz, the phase margins are almost the same. Generally speaking, it shows relationship between crossover frequency f_{bw} and t_r in Fig. 5 as $t_r = 1/4f_{bw}$ [2]. This relationship in the proposed circuit matches fine because f_{bw} is 100kHz and t_r is 2.2us. Also, cutoff frequency f_c of $H_d(s)$ is determined as about $1/\pi DT_{on}$ using Pade approximation. In Fig.10 (a), it is 1.2MHz so that T_{on} is 650ns. The phase change by $H_d(s)$ is not seen in Fig. 10 (b), but the phase margin is small in Fig. 10 (c) because duty ratio is large.

We also see that f_{bw} does not change much by duty ratio; due to we must be careful when designing it because the COT pulse width is changed by duty ratio.

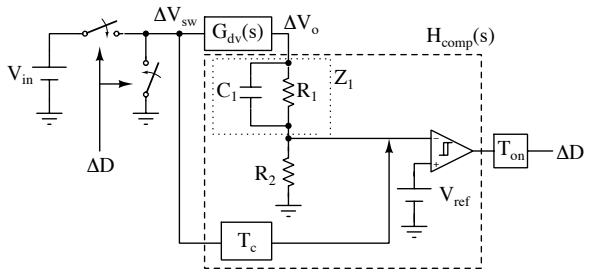
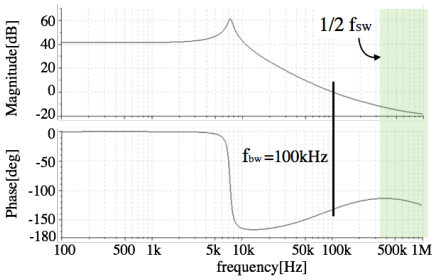
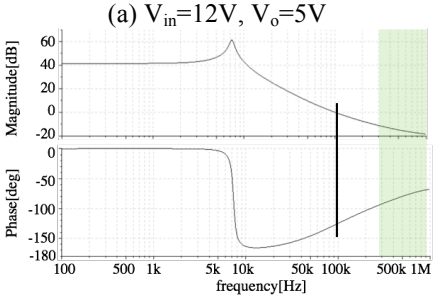


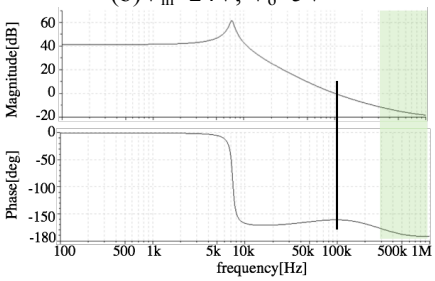
Fig. 9. Block diagram of the proposed circuit in Fig. 3[1]



(a) V_{in}=12V, V_o=5V



(b)V_{in}=24V, V_o=5V



(c)V_{in}=12V, V_o=10V

Fig. 10. Loop-gain obtained from the theoretical formula

5. Conclusion

We have proposed a constant frequency control method regardless of input/output voltage fluctuation and we have verified it by simulation. Steady state output voltage ripple and under/over-shoot voltages in response to the load change of the proposed method are at the same level as the conventional method. When V_{in} is varied from 10V to 24V, fluctuation of the switching frequency is suppressed from 58% to 6% and when V_o is varied from 2V to 6V, it is suppressed from 66% to 2%.

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