Dynamic Performance Improvement of DC-DC Buck Converter by Slope Adjustable Triangular Wave Generator

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Abstract

This paper describes a simple-yet-effective control method for a DC-DC buck converter with voltage mode control (VMC). We propose to use a slope adjustable triangular wave generator (TWG) which provides a line feed-forward control and an additional duty cycle modulation effect. Then comparing with the conventional VMC, the proposed method significantly improves the line and load transient responses. This triangular wave slope regulation scheme is simple compared to digital feed-forward control scheme that requires non-linear calculation. Our SIMetrix Simulation results show the effectiveness of the proposed method.

Keywords- slope regulation; triangular wave generator; buck converter; voltage mode control; transient response

Introduction

Continuous advancement of signal processing technologies for integrated circuits has posed stringent challenges to the transient response performance of switching power supplies, especially load transient response. A lot of research indicate that wideband of the control loop can obtain fast load transient respone [1-3]. VMC is easy to design and analyze, but its bandwidth is limited by the applied op-amp. Current mode control (CMC) is easy to obtain wideband, but an accurate current sensor and a slope compensation are required. Elaborate feed-forward control schemes have been proposed. However, their main drawback is the complexity of non-linear calculation [4,5] or limited performance in large load current transient condition [6].

This paper proposes a simple control method for VMC buck converter. This approach applies an adjustable TWG, and the slope of this triangular wave is regulated based on the input and output voltages. Therefore, we obtain not only line feed-forward control, but also load transient response improvement. The proposed method is simple and does not require a current sensor and complicated calculation.

Slope Adjustabe Triangular Wave Generator

A. System Configuration and Circuit

The proposed system block diagram is shown in Fig. 1. Op-amp1 is used to generate an error signal, where Type 3 compensation is incorporated and G_c denotes the gain. Op-amp2 senses and amplifies the output deviation by G_k, and its output works as control variable for the TWG; TWG is a time-variant function of the voltage, and it is reset every period by CLK pulse signal. The slope is decided by the control variable and the input voltage.

Fig. 2 shows the principle concept of the proposed TWG, where two completely consistent NMOSFETs M_1 and M_2 in the triode region are used to configure a linear voltage controlled resistor (VCR). The difference of two drain voltages is amplified and used to generate a proportional current signal by the voltage controlled current source (VCCS). Then this current signal is copied by the current mirror circuit. The capacitor C_T is charged by this current and reset by CLK signal. Therefore, the voltage across the capacitor is a triangular wave, which is given as

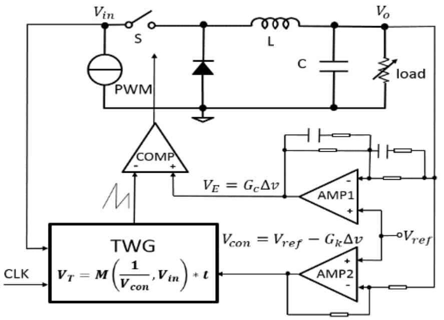


Fig. 1 DC-DC buck converter with a slope adjustable TWG.

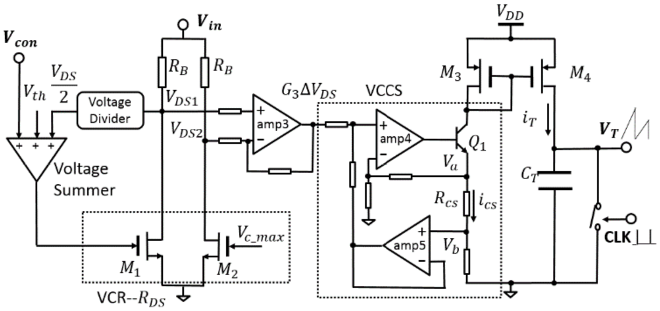


Fig. 2 Proposed triangular wave generator.

$$V_T = V_{in}\left(a\frac{1}{V_{con}} - b\right)t = M\left(\frac{1}{V_{con}}, V_{in}\right)t \qquad (1)$$

Where $a = \frac{G_3}{K_n R_B R_{CS} C_T}$, $b = \frac{a}{V_{c\_max}}$, $K_n = \mu_n C_{ox} W/L$, G_3 is the gain of amp3, V_{c_max} is the sum of the maximum control variable, V_{th2} and half of V_{DS2}. The slope is proportional to the input voltage and inversely proportional to the control variable (the output diviation).

B. Duty Cycle Modulation

Since the triangular wave slope is proportional to the input voltage, when the input voltage is changed, the peak value of the triangular wave is regulated. For the line transient response, the proposed method provides a line feed-forward control function.

For the load transient response of the VMC buck converter, the duty cycle modulation of the proposed method is shown in Fig. 3; the duty cycle variation is separated into two parts. $\Delta d_1 = \Delta t_{on1}/T_s$, which only depends on the slope variation and $\Delta d_2 = \Delta t_{on2}/T_s$ which is caused by the error signal and the slope.

Then the whole duty cycle modulation is obtained as:

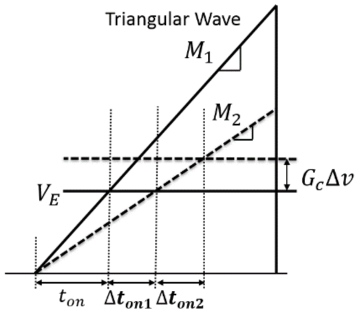


Fig. 3 Duty cycle modulation of proposed method.

$$\Delta d = \Delta d_1 + \Delta d_2 = \left(\frac{V_E}{T_s}+\frac{G_c\Delta v}{T_s}\right)\Delta\frac{1}{M}+\frac{G_c\Delta v}{T_s M_1} \qquad (2)$$

Substituting the slope function of eq. (1) into eq. (2), and ignoring the second-order non-linear terms, eq. (2) can be approximated as

$$\Delta d \approx \frac{bV_E G_k \Delta v}{T_s V_{in}(a-bV_{ref})}+\frac{G_c\Delta v}{V_{p\_static}} \qquad (3)$$

The first term is caused by the changed slope of the triangular wave, while the second term is just a conventional VMC. Therefore, with the same deviation in the output voltage, the proposed TWG provides faster and stronger regulation effect, which accelerates the transient response.

Simulation Results

Simulation conditions are shown in Table. 1. We have designed type 3 compensation for the conventional VMC buck converter to obtain 50kHz bandwidth and 40° phase margin.

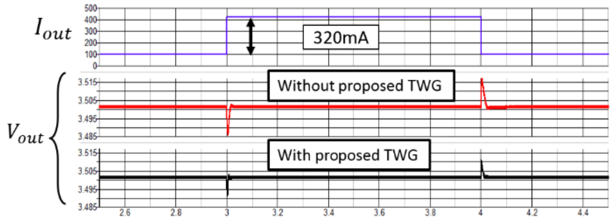
TABLE. 1 Simulation Conditions

Buck Converter Parameter	$V_{in} = 5V$, $V_{out} = 3.5V$, $V_{p\_static} = 3V$ $L = 10\mu H$ $(ESR = 10m\Omega)$, $C = 50\mu F (ESR = 10m\Omega)$, $R = 35\Omega$ $f_{switch} = 1MHz$, $H = 1$
Triangular Wave Generator	$G_k = 10$, $G_3 = 100$ $K_n \approx 3$, $C_T = 50pF$ $R_B = 1k\Omega$, $R_{cs} = 100\Omega$

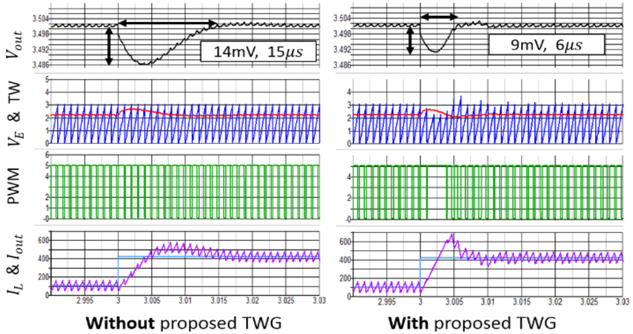
In our load transient response simulations with SIMetrix, the load current is changed stepwise between 100mA and 420mA. Simulation results of comparison with the conventional VMC buck converter are shown in Fig. 4. Thanks to the regulated triangular wave, the duty cycle is regulated as soon as the transient response happens. The additional effect provided by the proposed TWG prevents larger error signal development. Therefore, in step-up case, the under-shoot voltage is decreased from 14mV to 9mV, and the response time is shortened from 15μs to 6μs. In step-down case, the over-shoot voltage is decreased from 16mV to 10mV, and the response time is shortened from 20μs to 12μs.

Conclusion

This paper describes an adjustable triangular wave generator which can regulate the slope of triangular wave by the input voltage and the variation in the output voltage. The proposed method is very simple, and it does not need a current sensor and complicated calculation. Compared to the conventional VMC DC-DC buck converter, the proposed method improves both the line and load transient responses. For the line transient response, it works as a feed-forward controller to eliminate the change in input voltage. For the load transient response, the proposed method provides an additional control to the duty cycle, besides the effect of the error signal. This additional modulation effect accelerates transient response. We have verified the effectiveness of the proposed method with SIMetrix simulations.

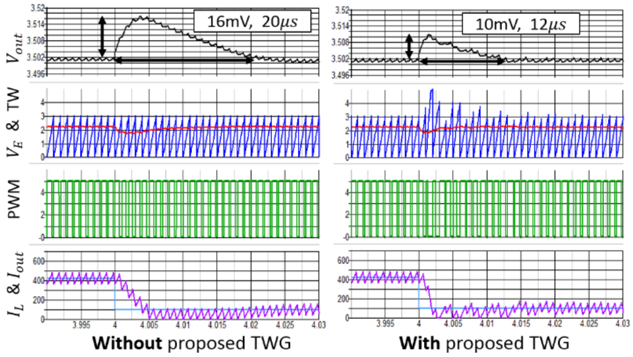


(a) Load transient response.



Without proposed TWG **With** proposed TWG

(b) Step-up



Without proposed TWG **With** proposed TWG

(c) Step-down

Fig. 4 Load transient responses (I_{out}: 100mA ↔ 420mA).

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