Continuous-Time Delta-Sigma Controller for DC-DC Converter

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1. Abstract.

This paper describes applications of a Delta-Sigma (ΔΣ) modulator to control a DC-DC converter. We propose to use a continuous-time (CT) feed-forward (FF) ΔΣ controller in a DC-DC converter and show that its transient response is faster than discrete-time (DT) and/or feedback-type (FB) ΔΣ controllers. We have also performed experiments of a DC-DC converter with a first-order continuous-time feedback ΔΣ controller and show its results.

2. Introduction

Recently the portable power management system landscape has changed due to an explosion in demand for portable devices such as cellular phones, personal digital assistants (PDA) and digital cameras. The DC-DC converter plays a crucial role in maintaining long battery life while providing a stable supply voltage and noise isolation. Most DC-DC converters use PWM controllers. However, rapid advances in power MOSFET devices have led to many researchers investigating the feasibility of ΔΣ modulators as controllers; the expected advantages over PWM controllers are as follows:

(1) Fast transient response
(2) High efficiency at low load
(3) Spread spectrum of switching noise
(4) Higher switching frequency operation with smaller L and C.

In this paper, we propose to use continuous-time (CT) feed-forward (FF) ΔΣ modulators, and we compare their performance with that of conventional DT and/or feedback (FB) alternatives. Compared with a DT ΔΣ modulator, the CT ΔΣ has benefits of low-power and high-speed [6-10]. Also compared with a FB ΔΣ modulator, the FF ΔΣ has better phase characteristics (in other words, fast response). These make the CT FF ΔΣ modulator more attractive as a controller for DC-DC converters.

3. Transfer Function Design of CT FF ΔΣ Modulator

Fig.1 shows block diagrams of DT and CT ΔΣ modulators, where Q denotes a quantizer. Since both discrete and continuous-time signals exist in the CT ΔΣ loop, we use the transformation between the discrete and continuous-time, based on the impulse response invariant transformation.

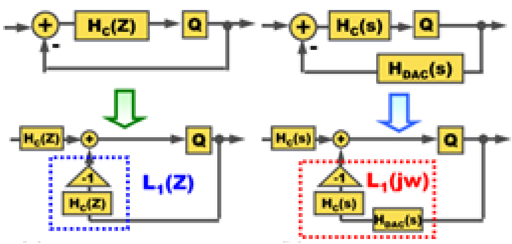

Fig. 1. DT and CT ΔΣ modulators.

For the first order ΔΣ modulator, we have

$$L1(z) = -(1/z)/(1-(1/z)).$$

Its impulse response g(nT) is given by

$$g(nT) = \begin{cases} 0 & \text{for } n < 0 \\ -1 & \text{for } n >= 0 \end{cases}$$

The impulse response of L1(jω) is obtained as follows:

$$h(t) = hc(t) * h_{DAC}(t).$$

Here * denotes convolution. A non-return-to-zero (NRZ) DAC is used as the DAC inside the ΔΣ modulator (that is the controller of the DC-DC converter).
Therefore,

$$h_{DAC}(t) = u(t) - u(t-T),$$

Where

$$u(t) = \begin{cases} 0 & \text{for } t < 0 \\ 1 & \text{for } t >= 0 \end{cases}$$

So we have

$$H_{DAC}(s) = (1\text{-}\exp(\text{-}sT))/s.$$

Suppose Hc(s) = A/s (where A is a constant), then we have

$$H(s) = Hc(s)H_{DAC}(s) = (A/s)\,[1\text{-}\exp(\text{-}sT)]/s.$$

Using the Laplace transform, we obtain the following:

$$h(t) = \begin{cases} 0 & \text{for } t <= 0 \\ A \cdot T & \text{for } t > 0 \end{cases}$$

Thus,

$$h(nT) = \begin{cases} 0 & \text{for } n <= 0 \\ A \cdot T & \text{for } n > 0 \end{cases}$$

Since the inverse Laplace transform of H(s), h(nT) is equal to g(nT), we can calculate A = -1/T.

Then we have

$$Hc(T) = \text{-}1/(sT).$$

Additionally, we can calculate FB CT ΔΣ signal transfer function as follows:

$$STF(s) = \text{-}\ Hc(s)NTF(s) = 1/(sT)\ [1\text{-}\exp(\text{-}sT)].$$

We can calculate CT FF ΔΣ signal transfer function (STF) as follows:

$$STF(s) = [1+ Hc(s)]\ NTF(s) = [1+1/(sT)]\ [1\text{-}\exp(\text{-}sT)]$$

Using Matlab software, we have obtained Bode plots for

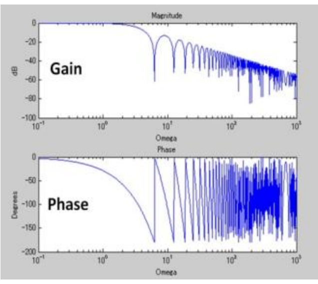

Fig. 2. First-order CT FB ΔΣ modulator STF Bode plot.

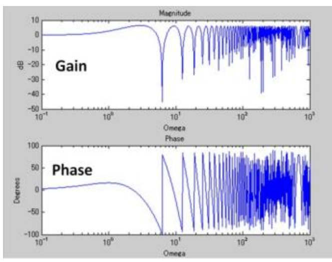

Fig. 3. First-order CT FF ΔΣ modulator STF Bode plot.

two types of ΔΣ modulators (Figs. 2, 3).

The phase delay of the FB ΔΣ modulator increases with angular frequency ω, but that of the FF ΔΣ modulator does not; this is an advantage of the FF ΔΣ modulator as a controller in a feedback system. Using the same calculation method, we can obtain the signal transfer function of the second-order ΔΣ modulator and we will observe that the second-order CT ΔΣ modulator shows better phase characteristics than the first-order one.

Note that the reader can refer to [2] for more information about second-order ΔΣ modulators.

4. Simulation results

In Section II, we showed a theoretical analysis of the CT ΔΣ modulator; we found that the CT FF ΔΣ modulator shows better phase characteristics than the FB one, and the 2nd-order CT ΔΣ is better than the first-order one. We used Simplis for simulation to validate the theoretical analysis in Section II, and compared the performance of PWM and various types of ΔΣ modulators as controllers for the buck converter. Table 1 lists the simulation parameters.

Our simulation results of steady state output voltage waveforms of buck converters controlled by PWM, first and second-order DT, CT FB, and FF ΔΣ modulators, show that

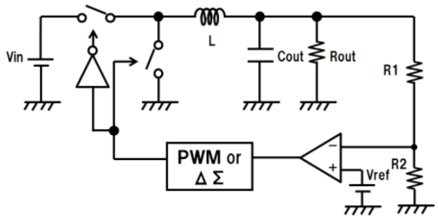

Fig. 4 Basic circuit for simulation.

Table.1. Simulation Parameters

Parameter	Value	Parameter	Value
Vin	12V	R1	1kΩ
L	22uH	R2	1kΩ
C	220uF	Vref	2.5V
R	10Ω	Fck	2MHz

the steady-state output voltage ripple of the buck converter controlled by PWM is the smallest. As for DT ΔΣ controllers, the 2nd-order type was superior to 1st-order, and the FF type was superior to the FB type, with smaller output ripple. However, the steady-state ripple of buck converters controlled by CT ΔΣ was almost identical.

Fig.5 shows load transient output voltage waveforms of buck converters controlled by various types of modulators. At time 10ms, the output load current is changed from 0.5A to 1.0A. The different colors stand for different outputs controlled by different modulators; the key to the colors is shown in Table 2.

We see that the output voltage controlled by the CT second-order FF ΔΣ reaches the steady state faster than any other, while the PWM response is the slowest.

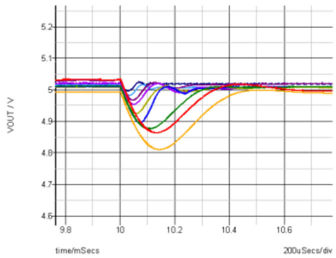

Fig. 5. Transient responses.

Table.2. Key to colors representing

Line	Modulator
	PWM
	DT first-order FB ΣΔ
	DT second-order FB ΣΔ
	DT first-order FB ΣΔ
	DT second-order FF ΣΔ
	CT first-order FB ΣΔ
	CT second-order FB ΣΔ
	CT first-order FF ΣΔ
	CT second-order FF ΣΔ

Remark:

(1) Our simulations show that the CT ΔΣ has faster transient response than the DT ΔΣ of the same order. This is because there is no delay from the input X(z) to the output Y(z) in the FF ΔΣ.

(2) Our simulations also show that the second-order ΔΣ controller has smaller output ripple and faster transient response performance than the first-order with the same-type of ΔΣ. This is because, in the second-order ΔΣ, the second-order noise-shaping function suppresses low-frequency components of E(z) significantly, and the LC circuit rejects its high-frequency components.

5. Experimental Results

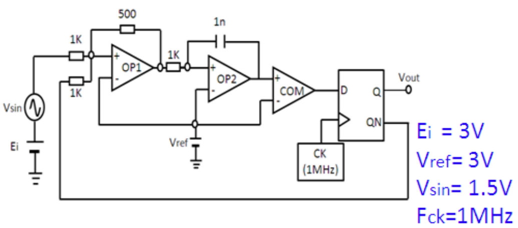

Fig.6. 1-bit CT FB type ΔΣ modulator

In this section, we show our experimental results of the first-order CT FB ΔΣ controller for DC-DC converter. Fig.6 and Fig.7 show the circuit diagram and waveforms of the first-order CT FB ΔΣ converter.

The channel 3 in the Fig.7 is the output of the converter. From the enlarged diagram we know that if Vin is higher than Vref, the number of pulse signals in channel 3 will increase; If Vin is lower than Vref, the number of pulse signals in channel 3 will decrease. Channel 3 is sent through a low-pass filter whose output is the channel 4

Fig.7. First-order CT FB type ΔΣ modulator waveforms.

signal. We found the channel 4 signal is very similar to the channel 1 signal. The only difference is that the channel 4 signal has a slight delay as shown in Fig 8. This result correlates well with the theory.

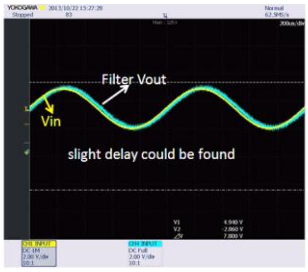

Fig.8. Channel 1 and channel 4 waveforms.

Next we will introduce first-order CT FB ΔΣ controller to DC-DC converter. First, we will show the single input single output (SISO) DC-DC converter properties, using the circuit shown in Fig.4. This is the steady state of SISO DC-DC

Fig.9. SISO DC-DC converter waveforms.

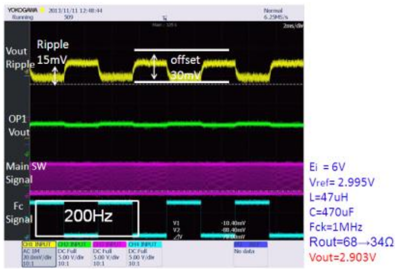

Fig.10. SISO DC-DC converter load response

converter, Vin is 6V and Vref is set at 2.970V in order to offset Vout. We will use phase lag compensation to reduce the offset. Vout ripple is low at only 10 mV. Compared to PWM control, the frequency of Main switch just 1/10 as the frequency of Fck. ΔΣ control has the advantage that it can reduce the number of switch action and the switching noise is smaller.

Fig.11. Phase lag compensation

The load response of the circuit is shown in Fig.10. When Rout is changed from 68 Ωto 34 Ω or vice versa, the Vout offset becomes worse and the ripple offset also appears. So we need to use phase lag compensation to reduce the offsets. The result of this is as shown in Fig.11, the Vout and ripples are what we want (15mV ripple and about 0mV offset).

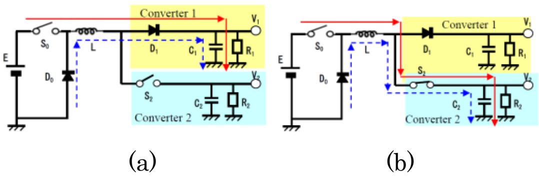

Fig.12. SIDO DC-DC converter principle.

Next, we will use a new control method to control the single-inductor dual-output (SIDO) DC-DC converter. The proposed buck-buck SIDO converter is shown in Fig.12, where the red solid line shows the direction of current flow when the inductor is charged, and the blue dashed line shows the current flow when the inductor is discharged. Fig.12 (a) shows the condition when converter 1 (V1) is selected to be controlled and Fig.12 (b) shows when converter 2 is controlled.

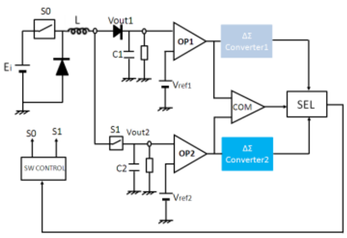

Fig.13. SIDO DC-DC converter. properties,

The circuit is shown in Fig 13, and its output response properties are shown in Fig 14 (self-regulation of converter 2 and cross-regulation of converter 1, when the Rout of converter 2 is changed from 22 Ω to 13 Ω or vice versa). Self-regulation of V2 and cross-regulation of V1 are about 10mVpp (excluding clock noise). The voltages of Vout1 and

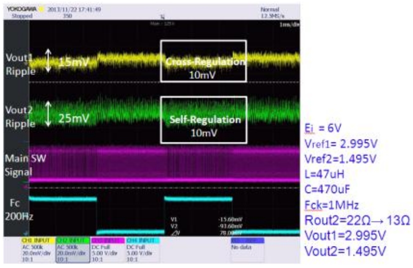

Fig.14. SIDO DC-DC converter output voltage ripples.

Vout2 may be acceptable, but the 10mV ripple offset needs to be suppressed.

6. Conclusion

This paper proposed using CT FF ΔΣ modulators as controllers for DC-DC converters. Compared with the PWM controller, the ΔΣ modulator can provide a faster return to the steady state when the load of the buck converter is changed. We showed in simulation that, as DC-DC converter controllers, the CT ΔΣ is superior to the DT modulator, the FF ΔΣ is superior to the FB one, and the second-order ΔΣ is superior to the first-order in fast transient response. We also showed the experimental results of the first-order CT FB ΔΣ converter and the DC-DC converter with the first-order CT FB ΔΣ converter.

7. References

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