Dynamic Characteristics of DC-DC Converters Using Digital Filters

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ABSTRACT

This paper presents the dynamic characteristics of buck and buck-boost dc-dc converters with digital filters. At first, the PID, the minimum phase FIR filter and the IIR filter controls are discussed in the buck dc-dc converter. Comparisons of the dynamic characteristics between the buck and buck-boost converters are then discussed. As a result, it is clarified that the superior dynamic characteristics are realized in the IIR filter method. In the buck converter, the undershoot is less than 2% and the transient time is less than 0.4ms. On the other hand, in the buck-boost converter, the undershoot is about 3%. However, the transient time is approximately over 4ms because the output capacitance is too large to suppress the output voltage ripple in this type of converter.

Keywords: Buck converter, Buck-boost converter, Digital control, FIR filter, IIR filter, Dynamic characteristics

1. Introduction

Switching power supplies has been receiving increasing attention in an effort to save energy and C_{O2}. Furthermore, in telecommunications systems, data communications systems and so forth, high controllability and monitoring function are required to improve reliability. In this case, digital control is useful because it has the advantage of realizing both control and monitoring tasks.

The digital control circuit is composed of an A-D converter and a control part which is usually constructed by a ASIC or DSP[1]-[4]. In this control circuit, the digital P-I-D control or the digital low-pass filter control algorithm has been programmed. So, these control methods have been reported[1],[5]-[8]. However, the output characteristics of these dc-dc converters have never been discussed in detail.

Especially, the relationship between the output characteristics of the digital filter method and the control parameters is unknown.

This paper presents the dynamic characteristics of the basic buck and buck-boost converters with digital filters. After reviewing the fundamental configuration of a digitally controlled dc-dc converter and its operation principle, we analyzed the dynamic characteristics of three types of digital control methods.   The comparison of dynamic characteristics of the P-I-D control method, FIR (Finite Impulse Response) filter method and IIR

(Infinite Impulse Response) filter method is examined. Lastly, the dynamic characteristics of the basic buck and buck-boost converters with the most suitable digital filter are considered. The key point of this paper is to describe the possibility of realizing a digitally controlled switching power converter using a DSP.

2. Circuit configuration and operation

Fig. 1 shows the block diagram of the proposed digitally controlled dc-dc converter using a DSP. In Fig. 2 they are examined. E_i is the input voltage, e_o is the output voltage and i_o is the output current in these figures.

T_r is the main switch, D is the fly wheel diode, L is the energy storage reactor, C is the output smoothing capacitor and R is the load. The output voltage e_o is sent to the A-D converter through the anti-aliasing filter and is converted into digital amount N_n. The relation between the input and output values of the A-D converter is given by equation (1) when it approximately shows the linear expression by considering the width of the quantization to be small.

$$N_n = G_{AD}e_o \qquad (1)$$

where n denotes an n-th switching cycle, and the digital amount N_n is a positive integer number. G_{AD} is a gain of the A-D converter.

The digital amount N_n is sent to the DSP. In the DSP, the numerical value N_{Ton} that corresponds to the on-time interval T_{on} is calculated.

The relation between the on-time interval T_{on} and the numerical value N_{Ton} is shown as follows;

$$\frac{T_{on,n+1}}{T_S} = \frac{N_{Ton,n+1}}{N_{Ts}} \qquad (2)$$

where N_{Ts} is a numerical value corresponding to the switching period T_s (=1/f_s). N_{Ts} is calculated in the PWM signal generation circuit which is composed of a digital comparator or a counter. According to the relation between the on-time interval T_{on} and the numerical value N_{Ton}, T_{on} is generated. This T_{on} regulates the output voltage e_o.

The numerical value N_{Ton} of each control method is represented as follows.

2.1 P-I-D Control Method

The on-time interval N_{Ton} of the P-I-D control circuit is represented as follows [9];

$$N_{Ton,n+1} = N_B - K_P(N_n - N_R) \\ - K_D(N_n - N_{n-1}) - K_I \sum(N_n - N_{INT}) \qquad (3)$$

where K_P, K_D and K_I are the proportional, differential and integral coefficients. N_B is the numerical bias value. N_R and N_{INT} are the numerical proportional and integral desired values, these values are shown as follows;

$$N_B = N_{Ts}(1 + r/R)\frac{e_o^*}{E_i} \qquad (4)$$

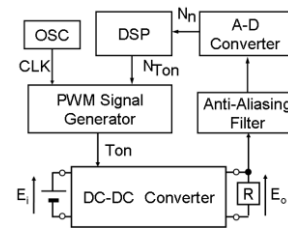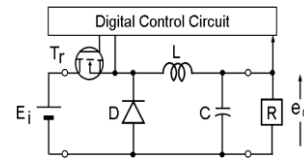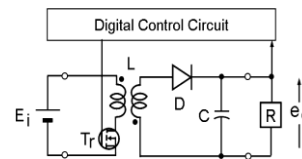$$N_R = N_{INT} = G_{AD}e_o^* \qquad (5)$$

Fig. 1. Block diagram of digitally controlled dc-dc converter using DSP.

(a) Buck dc-dc converter

(b) Buck-boost converter

Fig. 2. Basic dc-dc converters.

2.2 FIR Filter Control Method

The on-time interval N_{Ton} of the minimum phase FIR filter control circuit is represented as follows [10];

$$N_{Ton,n+1} = N_B - \sum_{i=0}^{q} h_i(N_{n-i} - N_R) \tag{6}$$

where h_i denotes the digital filter coefficients and q is the amount of the sampling points.

2.3 IIR Filter Control Method

The IIR filter is designed from an analog filter using the double primary conversion. The converted digital filter becomes the second-order IIR filters as shown in the next equation [11].

$$y_n = a_o x_n + a_1 x_{x-1} + a_2 x_{n-2} - b_1 y_{n-1} - b_2 y_{n-2} \tag{7}$$

where a_0, a_1, a_2, b_1 and b_2 are coefficients of the IIR filter, x_n is a difference between the digital value N_n and the desired value N_R. x_n is shown in the following equation.

$$x_n = N_n - N_R \tag{8}$$

Then, the on-time interval N_{Ton} of the IIR filter control circuit is represented by the following equation.

$$N_{Ton,n+1} = N_B - y_n \tag{9}$$

In a usual low-pass filter, a phase delay exists in the high frequency [10]. The phase delay sometimes causes unstable phenomena. So, to improve the delay of the phase, the differential element is added in this IIR filter. The stabilization of the dc-dc converter is attempted by this way.

3. Dynamic characteristics

3.1 P-I-D Control Method

Fig. 3 shows the experimental dynamic characteristics of the buck dc-dc converter with P-I-D control in step change of the load R from 50Ω to 10Ω. The input voltage E_i is 20V, the desired voltage E_o^* is 10V, the inductance L is $247\mu H$, the output capacitance C is $940\mu F$, and the number Q of bit of the A-D converter is 8bits, the dynamic range is from 0 to 20V corresponding

to the output voltage of the buck type dc-dc converter, respectively.

The sampling frequency f_{smp} in this case is 100kHz corresponding to the switching frequency f_s of the DC-DC converter. Furthermore, the other circuit parameters are f_s=100kHz, N_{Ts}=250, N_{RP} =N_{RINT} =127 and N_B =124. DSP is TMS320VC33. The calculation time of DSP is less than $4.1\mu s$.

The proportional coefficient K_P, the differential coefficient K_D and the integral coefficient K_I are 1.0, 1.0 and 0.01, respectively. The undershoot is over 200mV and the transient time T_{st} is 4.9ms. In this method, even if K_I is small and K_D is large, approximately 160mV is a minimum value [10] in the width of the vibration of the output voltage deriving from the limit cycle [11]. Therefore, this method is not suitable for the digitally controlled power dc-dc converter.

3.2 FIR Filter Control Method

Figure 4 shows the experimental dynamic characteristics in the minimum phase FIR filter control. The circuit parameters are the same as in Fig. 3 except for the data in Table 1.

Figure 5 shows the frequency characteristics of the FIR filter corresponding to Fig.4. In this method, the undershoot is over 200mV and transient time Tst is 2.7ms. Although the oscillation deriving from the limit cycle is suppressed, the transient response is not enough.

Table 1   Measured conditions corresponding to Fig. 4

| Passage Area Frequency (kHz)	5
Transition Area (kHz)	15
Passage Area Ripple (dB)	0.0
Quantity of Decrement (dB)	13

In Condition A through Condition D, gain G_2 and the second cut-off frequency f_c are assumed to be constant, and the gain G_1 is enlarged. When gain G_1 is enlarged, the first cut-off frequency f_a or the passing frequency f_c moves. In this case, it is designed so that f_a might reach a fixed value. It is seen in these figures that the steady-state error is suppressed because the first gain G_1

is enough high.
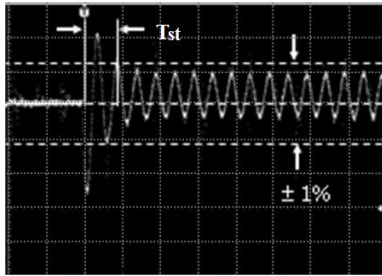
Vertical : 100mV/div., Horizontal : 4ms/div.

Fig. 3.   Indicial response of digital P-I-D control.
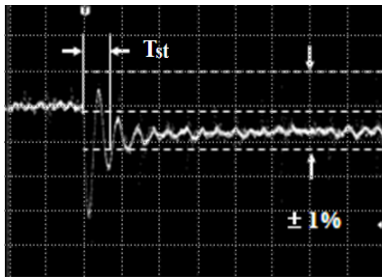
Vertical : 100mV/div., Horizontal : 4ms/div.

Fig. 4.   Indicial response of FIR filter method.
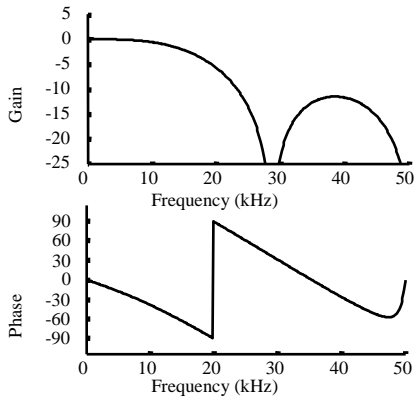

Fig. 5.   Frequency characteristics of FIR filter corresponding to Fig.4.
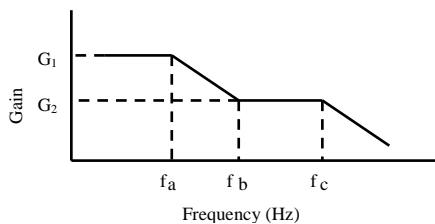

Fig. 6.   Definition of parameters in IIR filter.

Table 2   Parameters in each condition

	G_1 (dB)	G_2 (dB)	f_a(Hz)	f_b(Hz)	f_c(Hz)
Condition A	0	0	—	—	1k
Condition B	10	0	1	2.5	1k
Condition C	20	0	1	9.6	1k
Condition D	40	0	1	97	1k
Condition E	20	0	1	10.3	100
Condition F	20	0	1	9.6	10k
Condition G	40	0	0.1	10	10k
Condition H	40	15	1	10	40k
Condition I	40	20	1	17.5	40k

The experimental indicial response characteristics of the buck dc-dc converter in Condition A through Condition I are shown in Figs. 8(a) through (i). Moreover, Fig. 8 (d) shows the indicial response in Condition D.

In Figs. 8(a) through (g), the observed undershoot is from 3% to 4% and the observed transient time T_{st} is large. This numerical data is shown in Table 3. In these figures, the observed undershoot and the observed transient time T_{st} are not suppressed. However, in Figs. 8(h) and (i), the observed undershoot is less than 2% and the observed transient time T_{st} is less than 0.4ms as shown in Table 3. Moreover, when derived from the limit cycle suppression is adequate.

Table 3   Dynamic Characteristics of Buck Type Converter

Condition	Under Shoot(%)	Transient Time(ms)
A	3.03	5.06
B	2.89	7.04
C	3.27	7.32
D	3.52	21.47
E	3.92	18.05
F	2.90	2.91
G	3.13	5.06
H	1.76	0.34
I	1.31	0.38

In these conditions, gain G_1 and gain G_2 are enlarged, and then the second cut-off frequency f_c becomes high to maintain stability. f_c is less than half of the sampling frequency 100kHz. Especially, Condition H has a stable response characteristic compared with that in Condition

I because the second gain is too large under Condition I. Therefore, it is revealed that Condition H has superior characteristics.
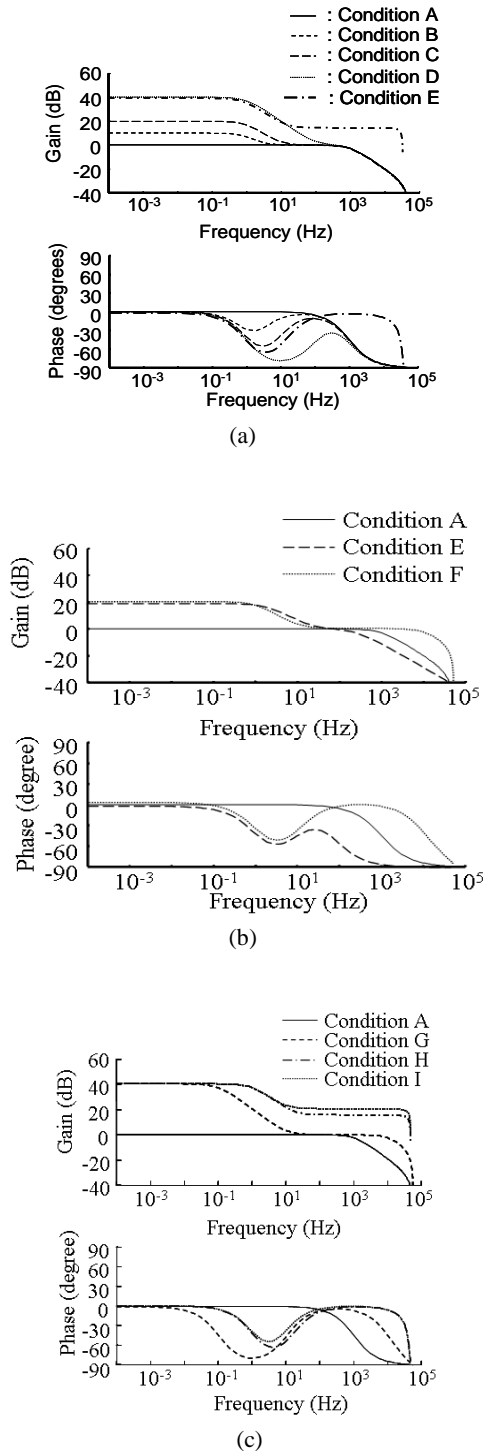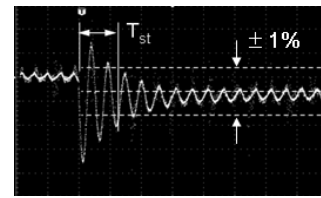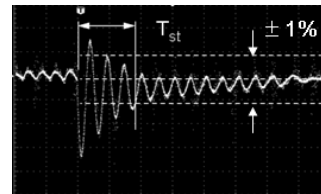

(a)

(b)

(c)

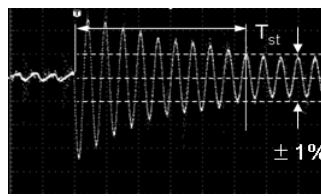Fig. 7.   Frequency characteristics in IIR filter.

(a)   Condition A

(b) Condition B

(c) Condition C

(d) Condition D

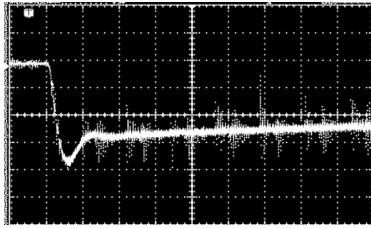Vertical : 100mV/div., Horizontal : 4ms/div.

Fig. 8.   Indicial response of buck converter with IIR filter.

Figures 9(a) through (i) show the experimental indicial response characteristics of the buck-boost dc-dc converter in Condition A through Condition I in Table 2. The inductance L is 260□ H, the output capacitance C is 1,880□ F, the input voltage is 10V and the others are the same as in Fig. 8.
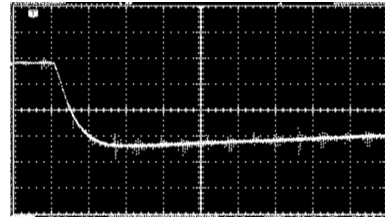
In Figs. 9(a) through (g), the observed undershoot and observed transient time T_{st} is large as shown in Table 4.

Table 4 Dynamic Characteristics of Buck-Boost Type Converter

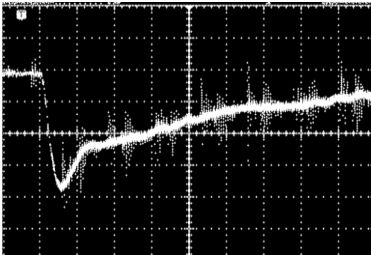| Condition	Under Shoot(%)	Transient Time(ms)
A	7.16	476.00
B	7.20	157.00
C	6.84	40.80
D	6.60	6.88
E	9.68	36.60
F	6.68	36.00
G	4.48	10.80
H	2.66	3.92
I	2.00	2.88

Vertical : 200mV/div, Horizontal : 4ms/div.

(a)   Condition A

Vertical : 500mV/div, Horizontal : 4ms/div.

(b) Condition B

Vertical : 200mV/div, Horizontal : 4ms/div.

(c) Condition C

Vertical : 200mV/div, Horizontal : 4ms/div.
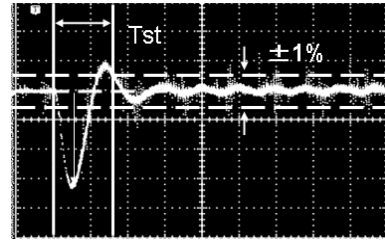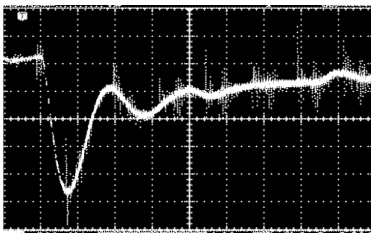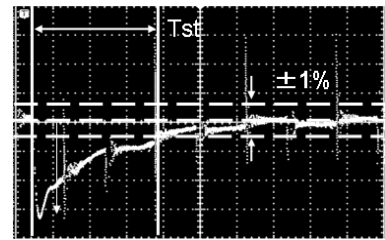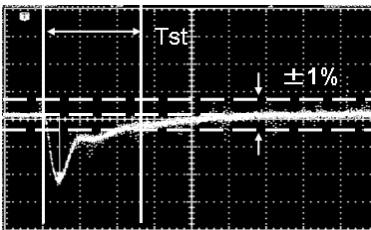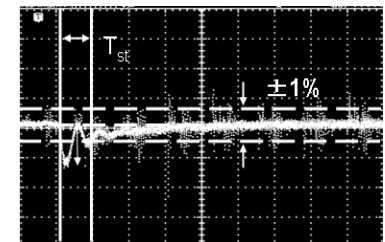
(d) Condition D

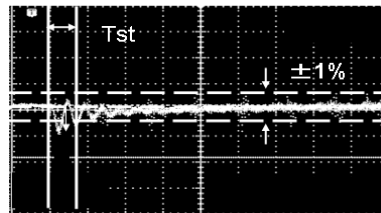Vertical : 200mV/div, Horizontal : 4ms/div.

(e) Condition E

Vertical : 200mV/div, Horizontal : 4ms/div.

(f) Condition F

Vertical : 200mV/div, Horizontal : 4ms/div.

(g) Condition G

Vertical : 200mV/div, Horizontal : 4ms/div.

(h) Condition H

Vertical : 200mV/div, Horizontal : 4ms/div.

(i) Condition I

Fig. 9.   Indicial response of buck-boost converter with IIR filter.

The undershoot is over approximately 5% and the transient time is over approximately 10ms. On the other hand, in Figs. 9(h) and (i), the observed undershoot is less than 3%, the observed transient time T_{st} is less than 4ms. Under Condition H, the observed waveform has stable transient response characteristics and vibrated phenomena are not observed. The transient time of the buck-boost converter is longer than that of the buck converter because the output capacitance of the buck-boost converter is too large to suppress the output voltage ripple and to maintain the stable state. The oscillation deriving from the limit cycle is also suppressed adequately in Condition H. Therefore, it is revealed that Condition H has also superior characteristics in the digitally buck-boost dc-dc converter with IIR filter.

These results suggest the design criterion of digital control circuit of switching power converters. It is concluded that the first gain G_1, the second gain G_2 and the second cut-off frequency f_c are relatively enlarged, and the first cut-off frequency f_a and the passing frequency f_b are relatively low in the IIR filter controlled switching dc-dc power converter as shown Condition H in Table 2. Moreover, it is important that the gain decreases at an extremely rapid rate at the second cut-off frequency f_c as shown in Fig. 7 because f_c is always less than half of the sampling frequency based on the sampling theory.

4. Conclusions

From the above discussion, it is revealed that the IIR filter control method has good dynamic characteristics. Furthermore, in the IIR filter, it is seen that the oscillation deriving from the limit cycle is suppressed in Condition H. It is concluded that the first gain G_1, the second gain G_2 and the second cut-off frequency f_c are relatively enlarged, and the first cut-off frequency f_a and the passing frequency f_b are relatively low. Moreover, it is important that the gain decreases at an extremely rapid rate at the second cut-off frequency f_c.

As a result, in the buck converter, the undershoot is less than 2% and the transient time is less than 0.4ms. On the other hand, in the buck-boost converter, the undershoot is about 3%. However, the transient time is approximately more than 4ms because the output capacitance is too large to suppress the output voltage ripple in this type of converter.

These results are very useful for realizing a digitally controlled switching power converter using a DSP.

Acknowledgment

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