A New Control Method for Buck-Boost DC-DC Converters Using Dual Σ⊿ Modulations for Mobile Equipment Applications

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Abstract—This paper presents a new approach to creating high-performance DC-DC converter systems for mobile-phone applications. The required supply voltage is 2.5V, and the output voltage of recent Lithium-ion secondary-batteries ranges from 4.2V to about 2V as they discharge. We have developed a bridge-configuration switching regulator that toggles between voltage-buck and voltage-boost modes, and maintains output voltage regulation even with a small input-output voltage differential. The time ratio of up or down conversion is changed continuously depending on load, and Sigma-Delta modulation is used to toggle between up or down conversion. At constant load, ripple is 6mVpp. Load regulation, corresponding to load current steps of ±0.5A or ±1.5A, is within 20mVpp or 45mVpp respectively.

Keywords：Switching Regulator, DC-DC Converter, Buck-Boost Converter, Σ⊿ Modulation

1. Introduction

There are many kinds of secondary batteries, and they are being continuously improved to increase their capacity. The output voltage of new high-capacity batteries varies over a wide range from the nominal supply voltage Vs as shown as Fig.1, so voltage buck-boost converter-regulators with small ripple and high efficiency are required to regulate the supply voltage. A bridge-configuration switching rectifier is suitable for realizing such buck-boost converters, because of its simplicity[1)]. However, it is difficult to maintain regulation when the input-output voltage differential is small. To realize this item, we propose to combine pulse-width-modulated Buck-Boost converters with Σ⊿ modulation used to toggle between buck and boost modes.

2. Buck-Boost Converter with full bridge circuit

Fig.2 shows the circuit of a bridge-configuration buck-boost converter. The voltage-buck (step-down) converter consists of S1, D1 and L, and the voltage-boost (step-up) converter consists of S2, D2 and L. L and Co comprise a low-pass filter, and R is the load resistor. For the voltage-buck converter, S2 is always OFF and S1 is switched on or off by a PWM signal from a controller. For the voltage-boost converter, S1 is always ON and S2 is switched on or off. In Continuous Conduction Mode(CCM), the voltage conversion ratio M can be expressed by Eq.(1) for the buck converter or by Eq.(2) for the boost converter.

$$M_D = Vo/Vi = T_{ON}/(T_{ON} + T_{OFF}) = D < 1 \quad (1)$$

$$M_U = Vo/Vi = (T_{ON} + T_{OFF})/ T_{OFF} = 1/(1-D) = 1/D' > 1 \quad (2)$$

Where Ton or Toff means the period of the switch ON or OFF, and D or D' means ON or OFF duty cycle of the switch.

This circuit needs a voltage differential ΔVi between Vi and Vo to convert correctly because of the voltage losses of the MOS switches, the diodes and the inductor. So the input voltage Vi should be greater than (Vo+ΔVi) for down-conversion and less than (Vo-ΔV) for up-conversion. In this paper we call this voltage range between (Vo+ΔVi) and (Vo-ΔV) the "non-controllable range". Usually when Vi > (Vo+ΔVi) or Vi < (Vo-ΔVi), the converter works in down or up mode respectively, and output voltage Vo is regulated to be close to Vs using a PWM signal from the controller. But for the non-controllable range, it is difficult to keep supply voltage Vo constant with small ripple.

3. Mixed U/D Control for Buck-Boost Converter with Bridge Configuration

3.1 Mixed U/D control with switching U/D ratio M:N

Fig.3 illustrates a mixed U/D control of buck/boost converter in the non-controllable range. In this range, the duty cycle of PWM is limited about to $D_D = 0.9$ in down mode and $D_U = 0.1$ in up mode, so we have developed a method of "mixed U/D control" which toggles continuously between Up and Down modes. In mixed U/D control, we choose the Up:Down (=M:N) ratio so that Vo is a little bit high. To reduce the output ripple when toggling U/D, either M or N is fixed at unity because the maximum peak of the ripple is nearly proportional to the number of the minor conversion. In this case, mixed U/D control is to stabilize the output voltage at Vs and the precise voltage control for ripple is done by PWM control.

In down mode the regulated voltage with $D_D = 0.9$ is $V_{DO} = 3.49V$ when Vi=4.0V and in up mode the regulated voltage with $D_U = 0.1$ is $V_{UO} = 3.91V$. So as Vi goes down, M:N ratio changes from 1:4 to 1:2, 1:1, 2:1 and finally 4:1. The theoretical value of Vo in mixed U/D control is shown as below.

$$Vo = (N^* V_{DO} + M^* V_{UO})/(M+N) \quad (3)$$

3.2 Characteristics of mixed U/D control [1]

Fig.4 shows the simulated characteristics of Vo with respect to changing the M:N step from 1:5 to 1:4 to

1:3 to 1:2 to 1:1 with constant duty ratio (D=0.9), keeping the input voltage constant. Each settled voltage for the M:N ratio is agrees well with (3). We see from this figure that the ripples at the U/D changing points are very small, and at the changing point of M:N ratio each overshoot is less than18mV. The maximum voltage of overshoot occurs at the changing M:N ratio from 1:1 to 2:1 or 1:2 vice versa.

From (3) the available input voltage range controlled by this method is from V_{DO} to V_{UO}. Using this mixed U/D control method, it is available to supply the stabilized output with small ripple in principle when the input voltage is in the non-controllable range.

Next we consider M:N control of a Buck-Boost Converter with D=0.9 fixed for non controllable input range. In this circuit the components are L=1.5μH, C=300μF, ESR (Equivalent Series Resistance) =50mΩ and R=5.0Ω (Io=0.5A). The frequency of the PWM signal is 500kHz, so the minimum period of the U/D control signal is 2us. The output voltage is stabilized at 2.25V for the input voltage from 4.7V to 1.1V as shown in **Fig.5**. In this figure, there is a voltage offset about 0.25V because of the low gain of DC feedback loop.

After DC gain up, the output voltage is stabilized at 2.5V, and the ripple is less than 10mVpp (peak-to-peak) when toggling between U/D control as shown in **Fig.6**. For load current steps of ⊿I=0.5A, 1.0A or 1.5A, the maximum overshoot is about 40mV peak.

4. Mixed U/D Control with Σ⊿ Modulation

4.1 Circuit of Σ⊿ modulation

The use of ΣΔ pulse-width modulation in DC-DC converters has already been investigated.[2)] **Fig.7** shows a first-order analog ΣΔ modulation circuit consisting of an integrator $1/(1-z^{-1})$, an adder, an analog-to-digital converter (ADC) and a digital-to-analog converter (DAC). The ADC and the DAC have 1-bit resolution, so it is very easy to realize them with a comparator, a latch and an inverter. But in this case, there appears the quantization noise Nq appearing at the ADC. Indicating the integrator as the equation $1/(1-z^{-1})$, the output signal y of this ΣΔ modulator is as shown below:

$$y = S - Nq, \quad S = (x-y)/(1-z^{-1}) \qquad (4)$$

Then

$$y = x - (1-z^{-1})\, Nq \qquad (5)$$

Where x is the input signal and z^{-1} means the delay of digital sampling (in this case: the latch).
From (5) the output y consists of the input x and the shaped noise $(1-z^{-1})\, Nq$. Here the noise shaping transforms low-frequency noise to higher frequencies. The relationship of the output to the input and noise is shown as below.

$$Y = x - (1-z^{-1})\, Nq \quad x - 4{*}SIN^2(\pi f/Fs){*}\, n_q \qquad (6)$$

where Fs is the ADC sampling frequency, which is synchronized with the PWM signal. **Eq.(6)** shows that the output signal is a regulated version of the input, while low-frequency noise is greatly reduced.

4.2 Characteristics of U/D control with Σ⊿ modulation

We investigate ΣΔ modulation instead of the M:N control because of the complexity to count the numbers of U/D control. To utilize Σ⊿ modulation for U/D control, switching U/D control is automatically decided to detect the output voltage. The ripple is less than 10mVpp when toggling between U/D control with Σ⊿ control as shown in **Fig.8**. For load current steps of ⊿I=1.5A, the overshoot is reduced less than 25mV peak, which is about half of that of the M:N control.

5. Control with Dual Σ⊿ Modulations

For DC-DC converter, it is reported to use Σ⊿ modulation instead of the PWM signal.[2] In our system, Σ⊿ modulation is used for the mixed U/D control in the uncontrollable range with PWM. Then we considered that it will be able to use Σ⊿ modulation both for U/D control in the controllable rang and for PWM signal in the uncontrollable rang as sown in **Fig.9**.

At first, we checked the principle of dual Σ⊿ modulations how to control the output voltage. To clear the control mode of pulses (Σ⊿1 and Σ⊿2) and to make the equivalent frequency up, the phase of the clock for Σ⊿ modulation is opposite each other (delayed 180 degree). **Fig.10**. In this figure, there are four modes with respect to ON/OFF of switches S1/S2. In mode Ⅰ(OFF/OFF), the capacitance C is discharged by the load current to make Vo down. Mode Ⅱ charges up C like a buck converter, and mode Ⅲ makes the current level higher like a boost converter but discharged like mode Ⅰ. Mode Ⅳ keeps the coil current as the previous mode without charging C.

From **Fig.10**, we understand that dual Σ⊿ modulations can control the output voltage in both controllable range and uncontrollable range. **Fig.11(A)** shows the output ripple is about 5mVpp when toggling with Σ⊿ controls as shown in **Fig.11(B)**. For load current steps of ⊿I=1.5A, the overshoot is about +30mV and -40mV peak.

6. Conclusions

We have developed a new method of controlling switched Buck/Boost DC-DC converters for mobile equipment. By toggling between up-control and down-control using Σ⊿ modulation, stable output with small ripple is realized in uncontrollable input range. Moreover we have proposed the method of dual Σ⊿ modulations for back-boost converter. In this case, the overshoot of the output voltage is about 40mV peak when changing the load current by ±1.5A .

Reference

(1) T.Furuya, Y.Kobori, T.tsugane and H.Kobayashi, "A study of Changed Control System for DC-DC Converters for the Portable Telephone Equipment", Technical Meeting on Electronic Circuits, IEE Japan, ECT-06-50, pp.61-66 (2006-3) (in Japanese)

(2) Y.Imamura, T.Tanaka and H.Yoshida, "About Characteristic of DC-DC Converter Controlled by Delta-Sigma Modulation", Technical Report of IEICE, EE2002-78, pp.80-94 (2003-02) (in Japanese)

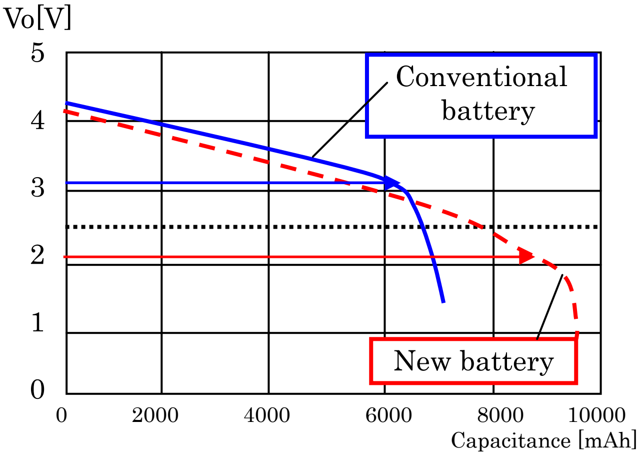


Fig.1 Characteristics of Lithium-Ion battery.

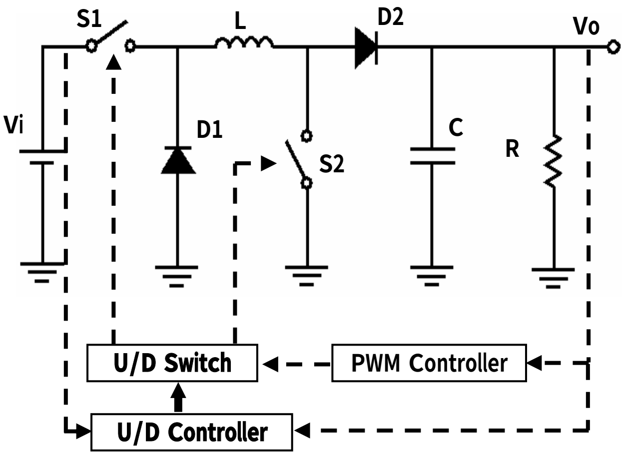


Fig.2 Full bridge DC-DC converter.

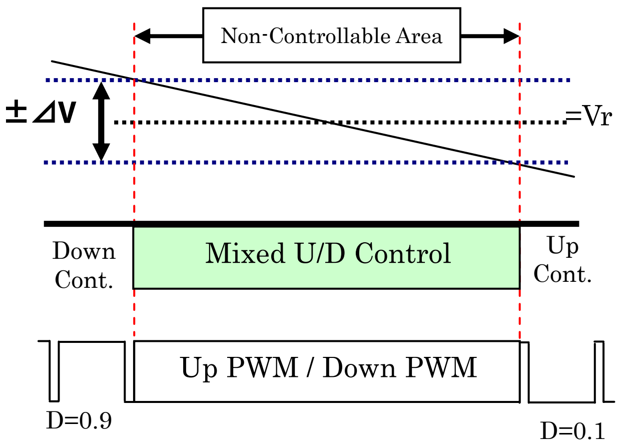


Fig.3 Illustration of mixed U/D control.

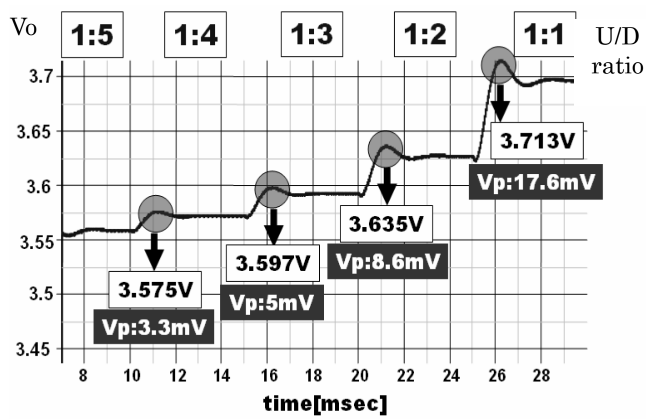


Fig.4 Characteristics of continuous M:N control.

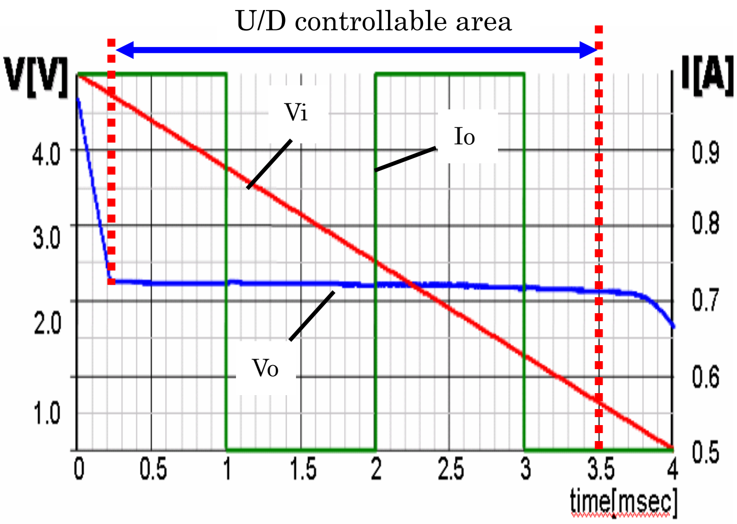


Fig.5. Vo characteristics with U:D control

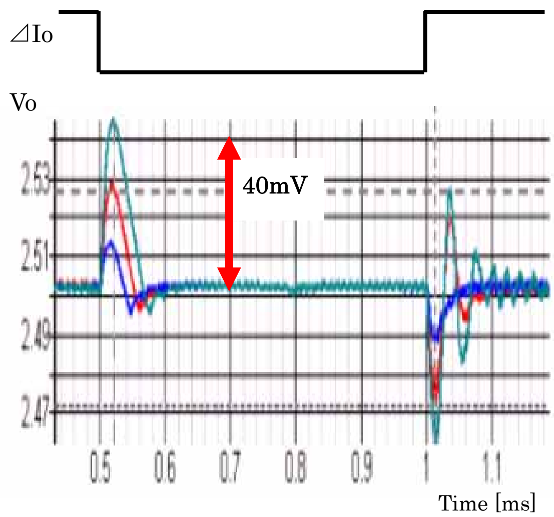


Fig.6 Vo Ripple with M:N ratio control

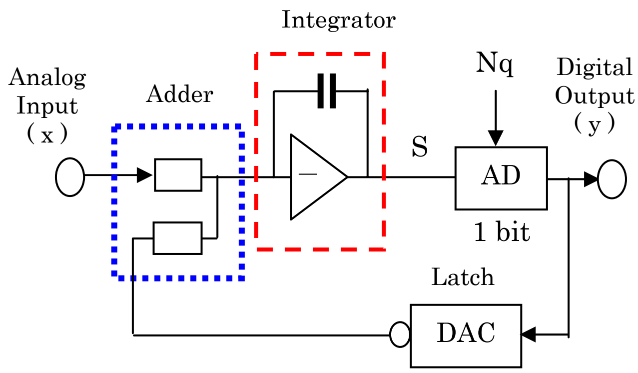


Fig.7 First-order Σ⊿ modulation circuit.

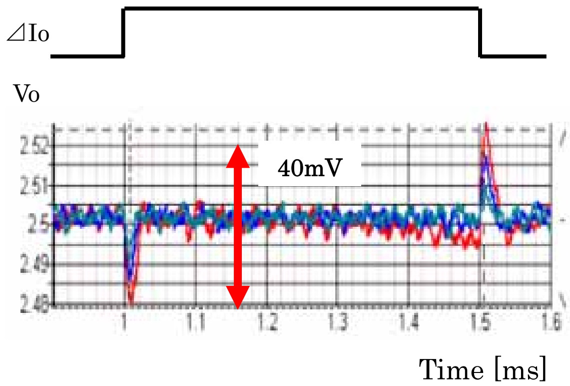


Fig.8 Ripple with Σ⊿ control

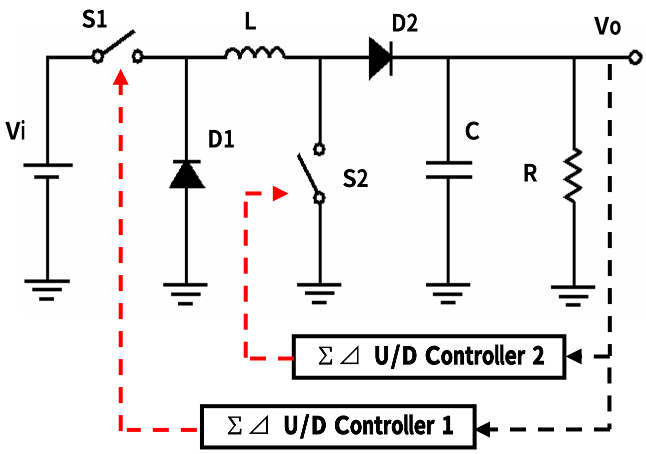


Fig.9 Converter with Dual Σ⊿ control

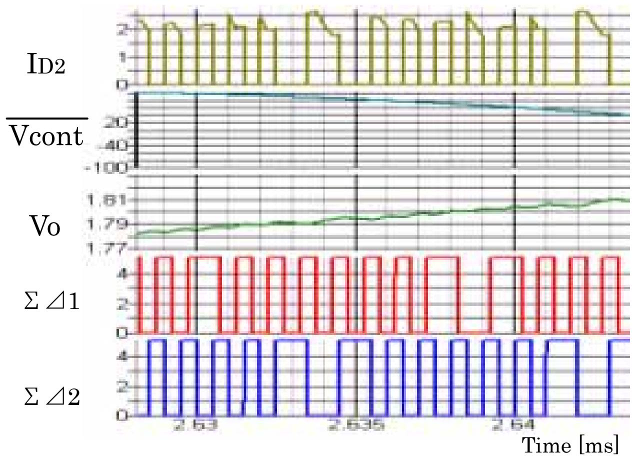
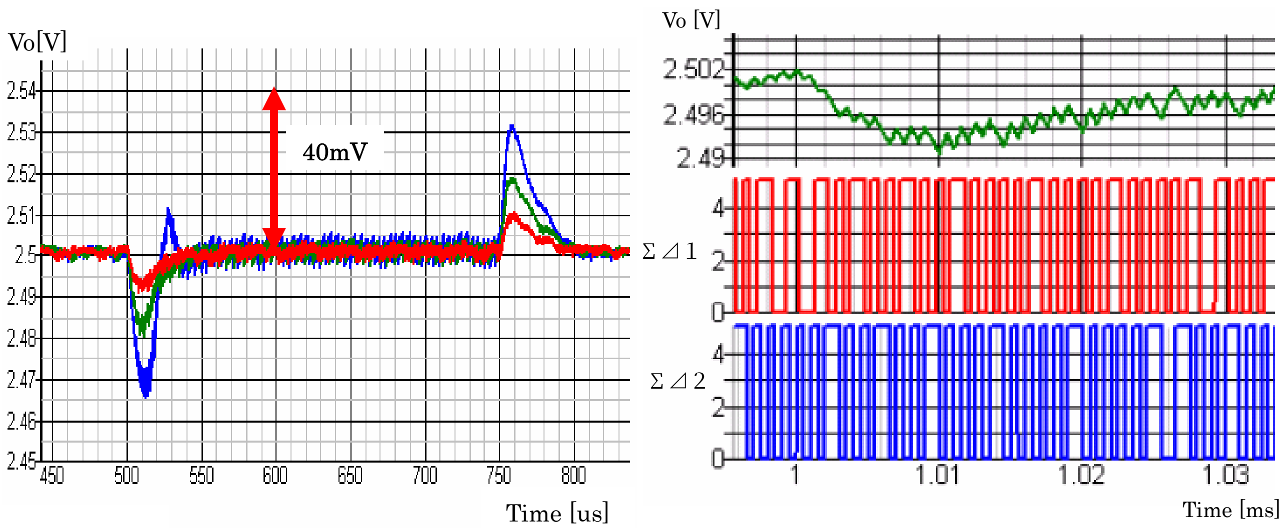


Fig.10 Characteristics of dual Σ⊿ control without feedback loop



(A) Ripple with ⊿Io=0.5～1.5A (B) Ripple and Σ⊿ Pulses with ⊿Io=0.5A

Fig.11 Characteristics of dual Σ⊿ control with feedback loop