Advanced Seamless Control for Buck-Boost Converters with Dual ⊿∑ Modulations

Yasunori Kobori*, Masashi Kono*, Haruo Kobayashi* and Toshihiko Shimizu**
* Electronic Engineering Department. Gunma University
E-mail: kobori@el.gunma-u.ac.jp
** Radio Frequency Analog Development Department, Renesas Technology Corp.
E-mail: shimizu.toshihiko@renesas.com

Abstract―This paper presents a new control circuit to create high-performance Buck-Boost converter for mobile-phone applications. The required supply voltage is 2.5V, and the input voltage from recent Lithium-ion secondary-batteries ranges from 4.2V to about 2V as they discharge. We have developed a bridge-configuration switching regulator with dual ⊿∑ modulations. To change the pulse frequency ratio for high side switch or low side switch automatically with ⊿∑ modulations, output voltage is regulated seamlessly. Experimental load regulation, corresponding to load current steps of ±0.5A, is within 45mVpp, and the efficiency is 83% at input voltage 2.5V and load current 0.8A.

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. However, it is difficult to maintain regulation when the input-output voltage differential is small. To realize this item, we have shown continuous changing of the mixed ratio of buck mode and boost mode. In this paper, we propose seamless control for two switches using dual ⊿Σ modulation, and show experimental results of output voltage ripples and efficiency.

2. Buck-Boost Converter with Mixed U/D Control

2.1 Buck-Boost converter with full bridge configuration

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.

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

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

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.

2.2 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.

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

3. Seamless Control with Dual ⊿Σ Modulators

3.1 Circuit of ⊿Σ modulator

The use of ⊿Σ modulator for PWM generator in DC-DC converters has already been investigated.[2] Usually ⊿Σ modulator circuit consists of an integrator, an adder, an analog-to-digital converter (ADC) and a digital-to-analog converter (DAC). In our first-order analog ⊿Σ modulator shown in **Fig.4**, D-latch is used for ADC and DAC because of the single bit resolution. The D-latch is clocked to detect the input D-level and output the single bit synchronized with the clock. In this case, there appears the quantization noise Nq at the ADC. Indicating the integrator as the equation $1/(1-z^{-1})$, the output signal y of this ⊿Σ modulator is as shown below:

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

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

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.

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

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.

3.2 Control with Dual ⊿Σ Modulators

For buck converter, it is reported to use single ⊿Σ modulation instead of the PWM signal.2) In our system, dual ⊿Σ modulators are used for high-side SW1 and low-side SW2 respectively as shown in Fig.5. These two ⊿Σ modulators work independently and the clock phases for them are reverse from each other. The states of two switches make 4 modes as shown in Fig.6. Mode 1 shows that SW1 and SW2 are both OFF. In this mode, the buttery is kept off from the inductance so the current of inductance become down to down. In the other hand, mode 3 shows that SW1 and SW2 are both ON and the buttery makes the current of inductance go up. Mode 2 or mode 4 is the state of keeping the inductance current almost constant.

In simulation, these 4 modes appear cyclically, for example, mode 1, mode 2, mode 3 and mode 4 or reversely. To control the output voltage higher, the period of mode 3 becomes wider to increase inductance current. To control the output voltage lower, the period of mode 1 becomes wider. The period of mode 2 or mode 3 is usually very little.

We use these dual ⊿Σ modulators in the circuit of a bridge-configuration buck-boost converter. For the step of the load current at ⊿Io=1.5A, the output voltage ripple is 70mVpp as shown in green characteristics in Fig.7.

3.3 Improvement of output voltage ripple

The green characteristics of output voltage ripple in Fig.7 is a little bit large, so we tried to reduce this ripple, but it was very difficult because the parameters of phase compensation in the amplifiers are almost same. So we have adjusted these parameters of each ⊿Σ modulator to minimize the output voltage ripple. For positive ripple that occurs because of the down step of the load current, it's good to adjust ⊿Σ modulator 1. For negative ripple because of the load current up step, ⊿Σ modulator 2 is adjusted. Because of this adjusting, the output voltage ripple become 35mVpp as shown in red characteristics in **Fig.7**.

4. Experimental characteristics of Buck-Boost Converter with Dual ⊿Σ Modulators

4.1 Ripple and Offset for Load Current Step

Fig.8 shows the output voltage ripple when the load current step is 0.25A. There is very small offset about 2mV and the peak noise about 15mVpp at the current transient. In this case, the frequency of the clock is 1 MHz and the period of current step is 50ms.

Then we checked the closed loop characteristics of our Buck-Boost converter with dual ⊿Σ modulators shown in **Fig.9**. The cut-off frequency is about 3.0kHz and the phase margin of this converter is about 28dB, enough to be stabilized.

4.2 Efficiency

The efficiency is one of the most important item for voltage regulators. We measured some efficiencies against load current, input voltage and clock frequencies using discrete circuit without synchronous rectifier. **Fig.9** shows the efficiency against the load current. The maximum efficiency is appeared near the load current 0.9A. In this figure, the black or red circle shows the efficiency of buck converter or boost converter of our circuit (by reducing unnecessary switch or diode). Buck converter has the best efficiency as you know.

Fig.10 shows the efficiency against the input voltage and **Fig.11** shows the efficiency against the clock frequency. **Fig.10** shows the interesting result that the efficiency is the best where the input voltage is 2.5V, that means the power loss is least at almost center of buck-boost conversion.

5. Conclusions

We have developed a new method of controlling switched Buck-Boost converters for mobile equipment. Using independent dual ⊿∑ modulations, stable output with small ripple is realized in uncontrollable input range. Moreover we have got 83% efficiency at input voltage and output voltage 2.5V and load current 0.9A without the synchronous rectifier.

Reference

(1) Y.Kobori, T.Furuya, M.Kono, T.Shimizu and H.Kobayashi, "A new Control Method for Switched Buck-Boost DC-DC Converters with Delta-Sigma Modulation for Mobile Equipment", 2006 Int'l Symposium On Intelligent Signal Processing and Communication System (2006)

(2) Y.Kobori, T.Furuya, M.Kono, T.Shimizu and H.Kobayashi, "A new Control Method for Buck-Boost DC-DC Converters Using Dual ∑⊿ Modulations for Mobile Equipment Applications", IEEJ 2006 Analog VLSI Work Ship (2006.)

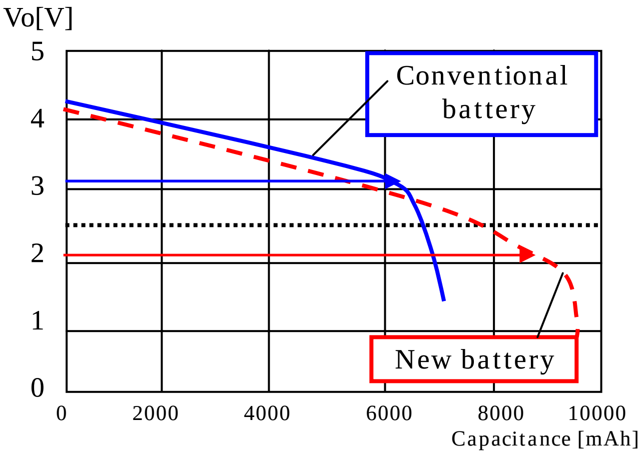

Fig.1 Characteristics of Lithium-Ion battery.

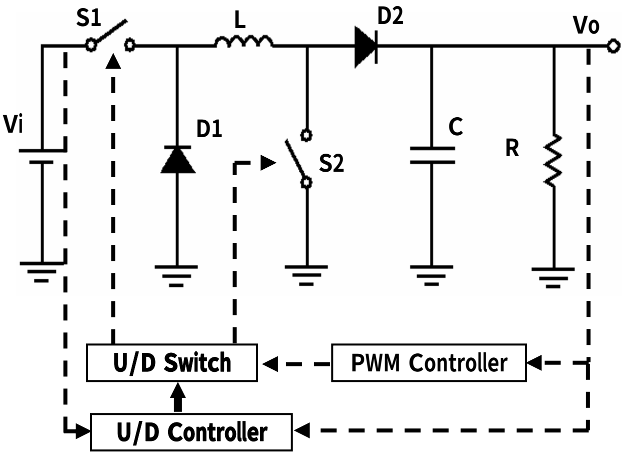

Fig.2 Full bridge DC-DC converter.

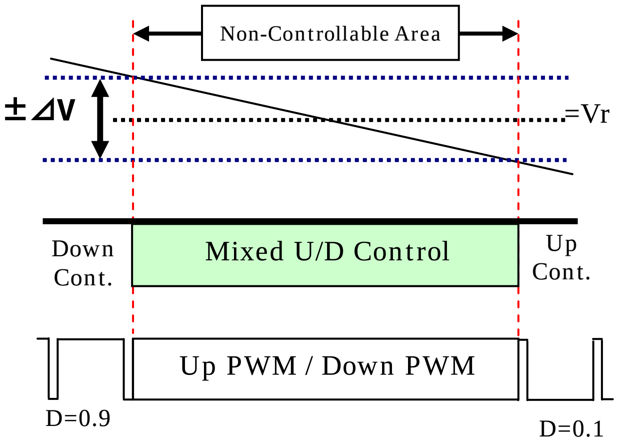

Fig.3 Illustration of mixed U/D control.

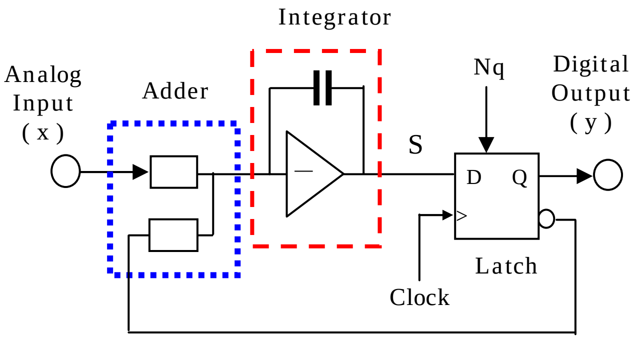

Fig.4 First-order ⊿Σ modulator circuit.

1 bit

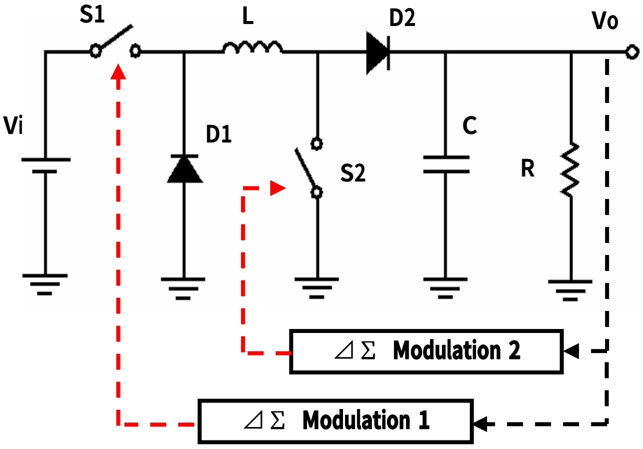

Fig.5 Converter with Dual ⊿Σ control

mode	1	2	3	4
SW1	OFF	ON	ON	OFF
SW2	OFF	OFF	ON	ON
I_L	Down	keep	Up	keep

Fig.6 Inductance current I_L with SW modes

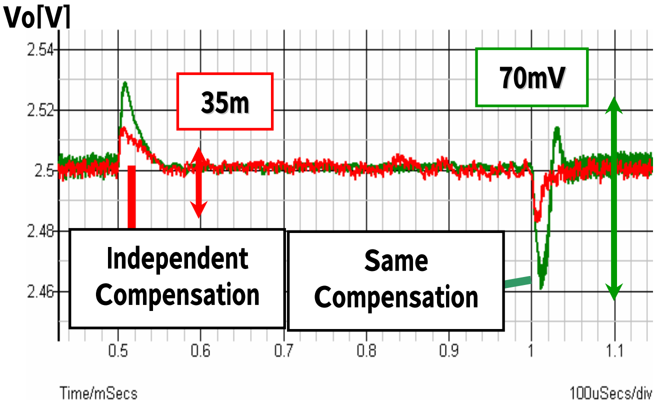

Fig.7 Improvement of Output Voltage Ripple

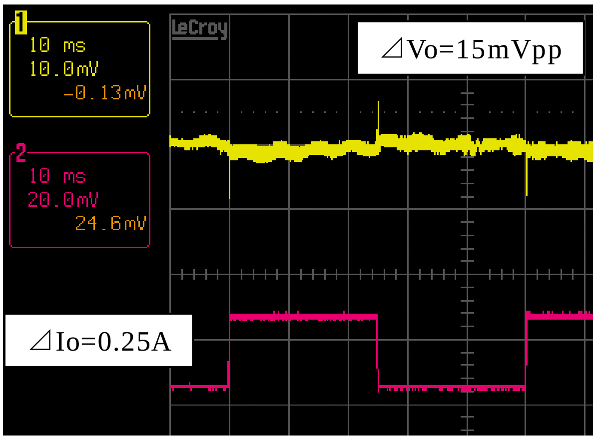

Fig.8 Ripple of Output Voltage

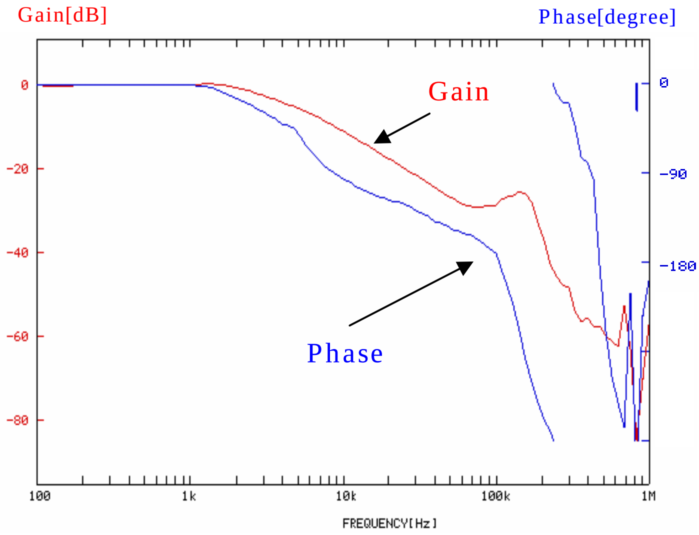

Fig.9 Closed Loop Characteristics

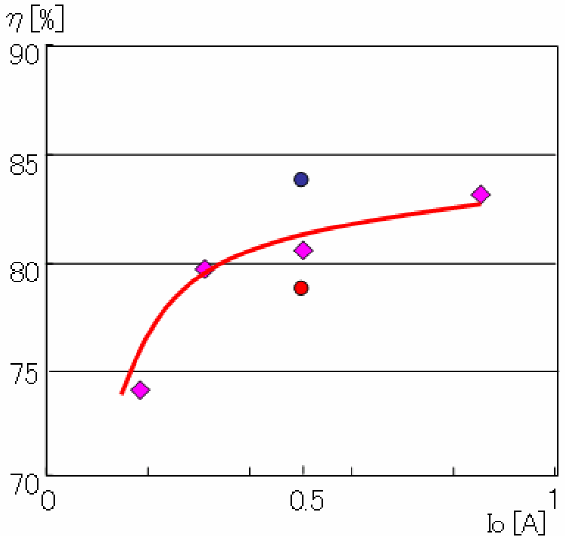

Fig.10 Efficiency vs Output Current

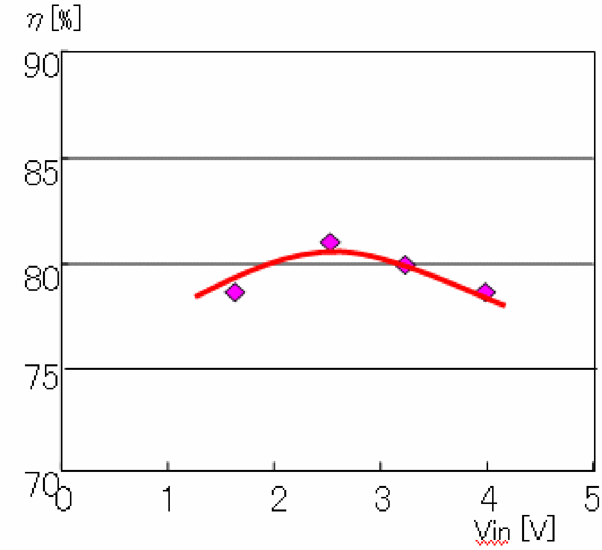

Fig.11 Efficiency vs Input Voltage

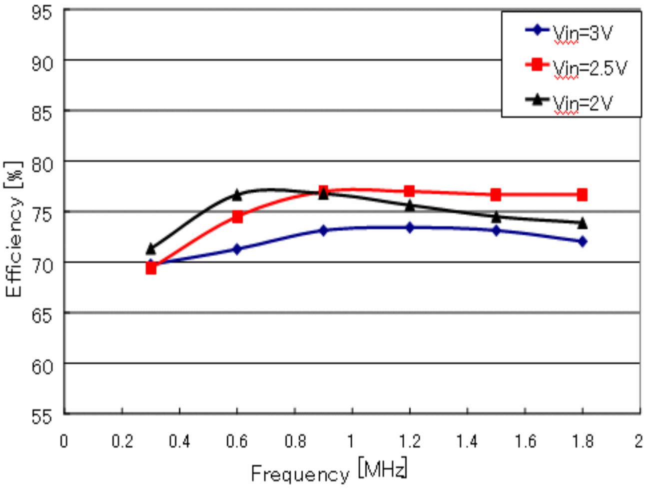

Fig.12 Efficiency vs Clock Frequency