Invited Paper

Advanced Non-Inverted Buck-Boost Converters using ⊿∑ Modulation

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Keywords: switching regulator, DC-DC converter, Buck-Boost converter, delta sigma modulation, feedback control, seamless voltage control, voltage ripple, secondary batteries

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 Delta-Sigma 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.

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 Delta-Sigma modulations, and show experimental results of output voltage ripples and efficiency.

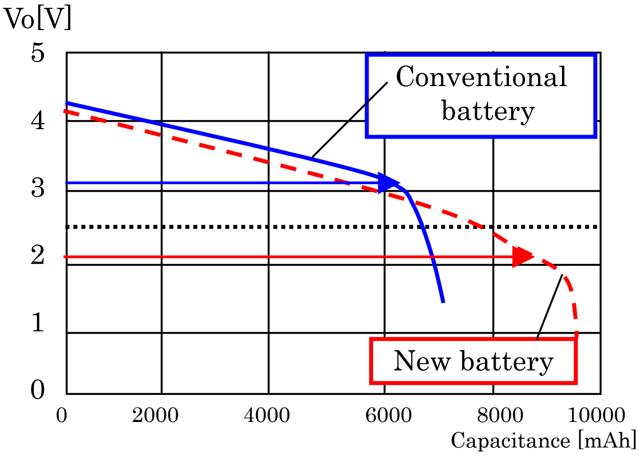

Fig.1 Characteristics of Lithium-Ion battery.

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 $(Vo+\Delta Vi)$ for down-conversion and less than $(Vo-\Delta V)$ for up-conversion. In this paper we call this voltage range between $(Vo+\Delta Vi)$ and $(Vo-\Delta V)$ the "non-controllable range". Usually when $Vi > (Vo+\Delta Vi)$ or $Vi < (Vo-\Delta Vi)$, 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.

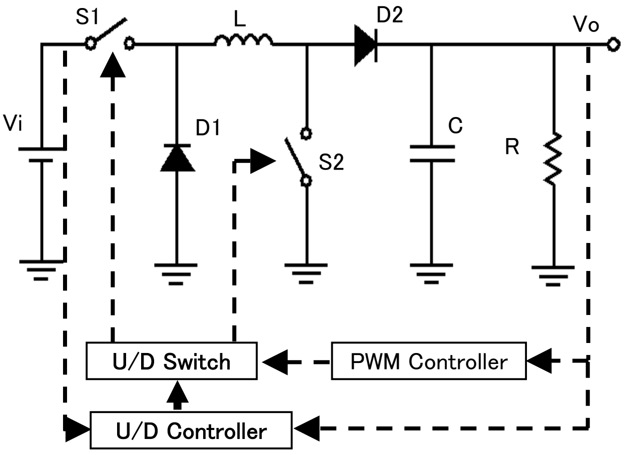

Fig.2 Full bridge DC-DC converter.

Mixed U/D Control with Switching Up/Down 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

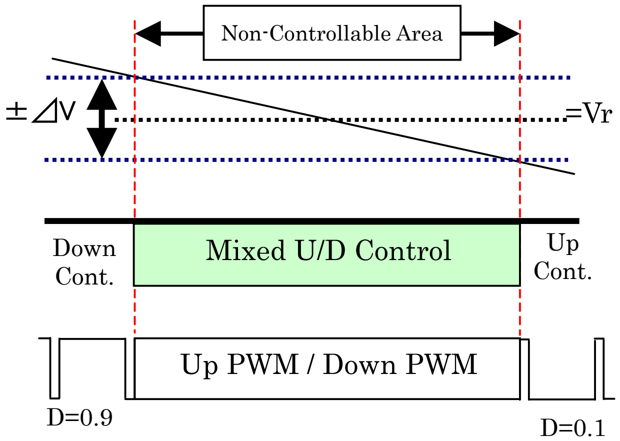

Fig.3 Illustration of mixed U/D control.

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.

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

Circuit of Delta-Sigma Modulation

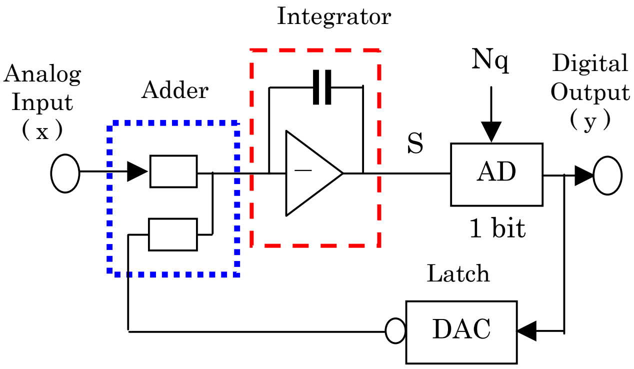

Fig.4 First-order Σ⊿ modulation circuit.

The use of Delta-Sigma pulse-width modulation in DC-DC converters has already been investigated.[2)] **Fig.4** shows a first-order analog Delta-Sigma 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:

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

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

Here, x is the input signal and z^{-1} means the delay of digital sampling (in this case: the latch). From Eq. **(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.

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

here 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.

Control with Dual Delta-Sigma Modulations

For buck converter, it is reported to use single Delta-Sigma modulation instead of the PWM signal.[2)] In our system, dual Delta-Sigma modulation is used for high-side SW1 and low-side SW2 respectively as shown in **Fig.5**. These two Delta-Sigma modulation circuits work independently ,and the clock phases for these circuits 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 becomes 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 Delta-Sigma modulations 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**.

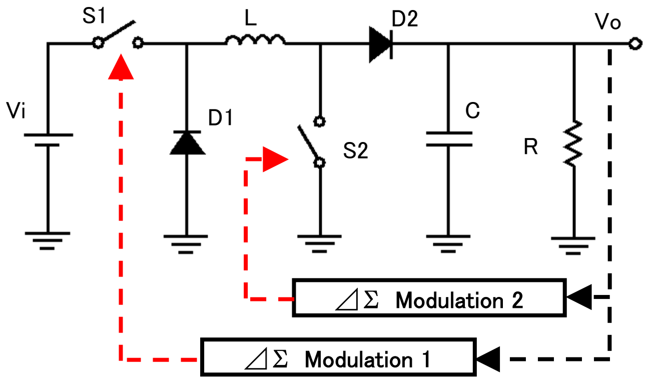

Fig.5 Converter with Dual ⊿Σ control.

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.

Improvement of Output Voltage Ripple

The green characteristics of output voltage ripple in **Fig.7** are 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 Delta-Sigma modulation 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 Delta-Sigma modulation 1. For negative ripple because of the load current up step, Delta-Sigma modulation 2 is adjusted. Because of this adjusting, the output voltage ripple becomes 35mVpp as shown in red characteristics in **Fig.7**.

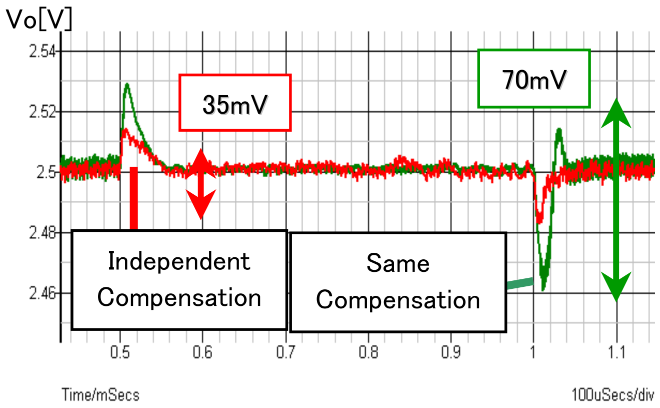

Fig.7 Improvement of Output Voltage Ripple.

Efficiency of Experimental Circuit with Dual Delta-Sigma Modulations

The efficiency is one of the most important items for voltage regulators. We measured some efficiency against load current, input voltage and clock frequencies using discrete circuit without synchronous rectifier. **Fig.8** 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.9 shows the efficiency against the input voltage and **Fig.10** shows the efficiency against the clock frequency. **Fig.9** 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.

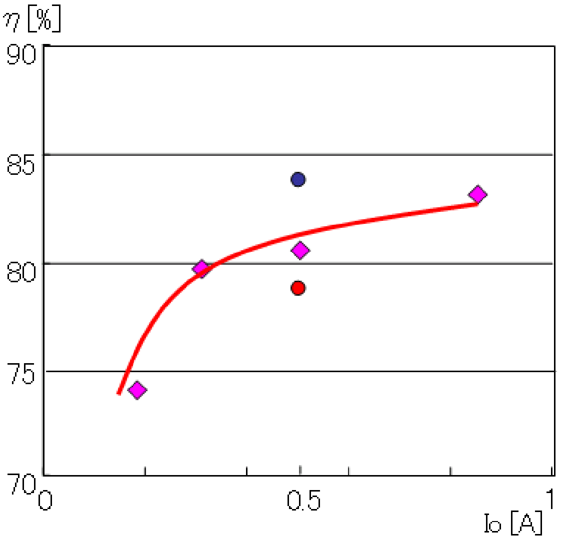

Fig.8 Efficiency vs Output Current.

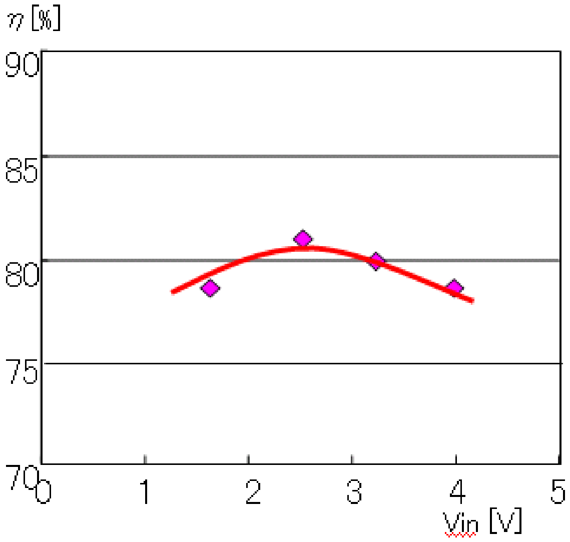

Fig.9 Efficiency vs Input Voltage.

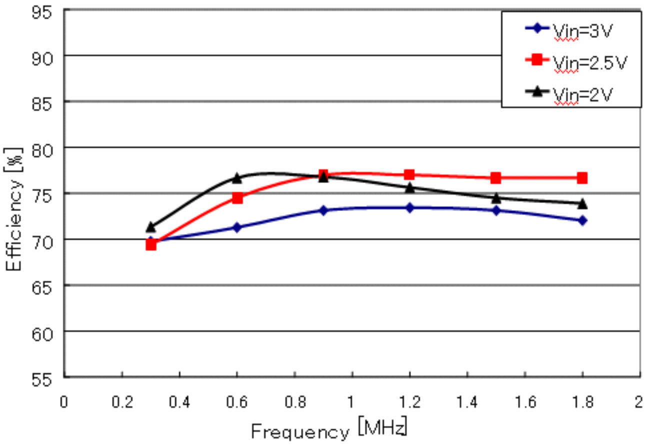

Fig.10 Efficiency vs Clock Frequency.

Possible Collaborations with Others

Switching voltage regulators like DC-DC converters or AC-DC converters are primary used in all electrical equipments. Usually they work for voltage power supply to circuits, CPUs, memories, motors etc. There are many voltage regulators in a system, which make a power train. On the other hand, some on-chip charge pump regulators are reported to control the voltage for the varistors.

(1) Collaboration with the on-chip voltage regulation technology

For the needs of the higher voltage than the normal voltage supply on a chip, it is one of the solutions to make the switching regulators on the same chip. In this situation, the cooperation with the circuit technology and LSI technology is desired.

(2) Collaboration with the motor driving technology

To decrease total power consumption, motor driving technology is very important. The efficiency of the driving circuit is the important factor which directly influences the battery performance. The systematic motor driving technique combined with power supplies is desired.

(3) Collaboration with the Delta-Sigma modulation technology

The Delta-Sigma modulation technology is used in many kinds of circuits like Analog-to-Digital converters, signal processing and servo motor controls. The precise control technology with Delta-Sigma modulation is desired.

(4) Collaboration with power control application fields

The power control is the key technology for the system design of the power consumption. The developed control strategies will be effective.

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Yasunori KOBORI received the B.S. and Ph.D. degrees from the Tokyo Institute of Technology in 1974 and 2000, respectively. From 1974 to 2001, he worked for Hitachi, and researched for the servo control system of VTR and video printing system. In 2002, he joined the Department of the Information Engineering of Matsue National College of Technology, Shimane, Japan. He joined the Department of Electrical and Electronic Engineering of Gunma University, Gunma, Japan in 2004 as Guest Professor.

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