ISPACS 2006

2006 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS2006)
Yonago Convention Center, Tottori, Japan

A New Control Method for Switched Buck-Boost DC-DC Converters with Delta-Sigma Modulation for Mobile Equipment

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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. It uses delta-sigma modulation, switches smoothly between voltage-buck and voltage-boost modes with ±6mV ripple (at constant load), and load regulation is within ±20mV for a load current step of 0.5A.**

1. INTRODUGTION

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 about 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.

2. BUCK-BOOST CONVERTER WITH FULL BRIDGE CIRCUIT

Fig.2 shows the circuit of a bridge-configuration buck-boost converter. Voltage-buck (step-down) converter consists of

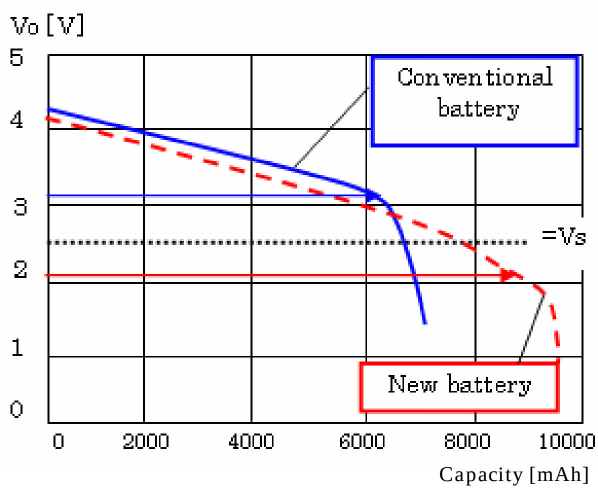

Fig.1. Characteristics of Lithium-Ion battery

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S1, D1 and L, and voltage-boost (step-up) converter consists of S2, D2 and L. L and C comprise a converter consists of S2, D2 and L. L and C comprise a low-pass filter, and R is the load resistance. 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.

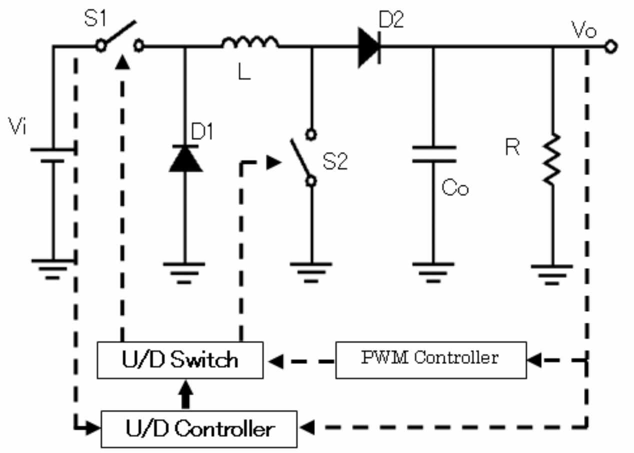

Fig.2. Bridge DC-DC converter

In Continuous Conduction Mode (CCM), for buck converter the voltage conversion ratio can be expressed by

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

and for boost converter.

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

Here D is ON duty cycle and D' is OFF duty cycle. These equations mean that Vo should be lower than Vi in down-conversion, and be higher than Vi in up-conversion.

This circuit needs a voltage differential dVi 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+dVi) for down-conversion and less than (Vo-dV) for up-conversion. In this paper we call this voltage range between (Vo+dVi) and (Vo-dV) the "non-controllable range." Usually when Vi > (Vo+dVi) or Vi < (Vo-dVi), 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.

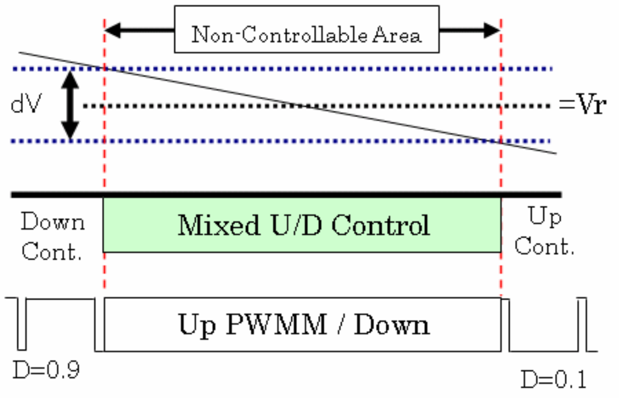

Fig.3. Illustration of mixed U/D control

3. Mixed U/D Control with Switching U/D Ratio

Fig.3 illustrates mixed U/D control of buck/boost converter in the non-controllable range. In this range, the duty cycle of PWM is limited, for example, to D_D =0.95 in down mode and D_U =0.05 (or D_U'=0.95) 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 ripple of the output voltage, either M or N is fixed at 1. In this case, V_{DO} in Down mode with D_D =0.95 is V_{DO}=3.49V and V_{UO} in Up mode with D_U =0.05 is V_{UO}=3.91V. So as Vi goes down, M:N ratio

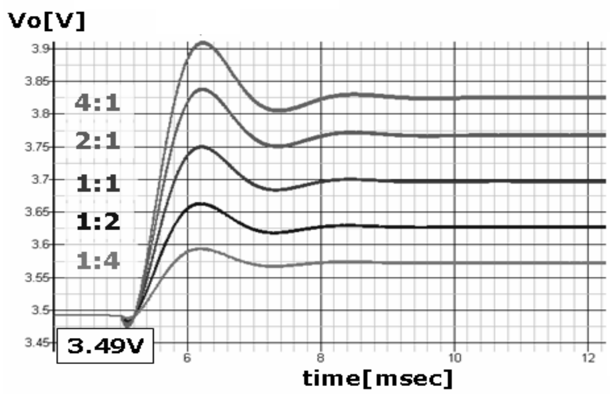

Fig.4. Characteristics of U/D control

changes from 1:4 to 1:2, 1:1, 2:1 and 4:1. The theoretical value of Vo in mixed U/D control is shown as below.

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

Fig.4 shows the simulated characteristics of Vo with respect to U/D ratio. This agrees well with (3). We see from this figure that overshoot is large, especially at M:N=4:1, because the initial M:N step was set for down control with D_D=0.95. If we change the M:N step continuously, however, the overshoot can be reduced to less than 20mV as shown in **Fig.5**.

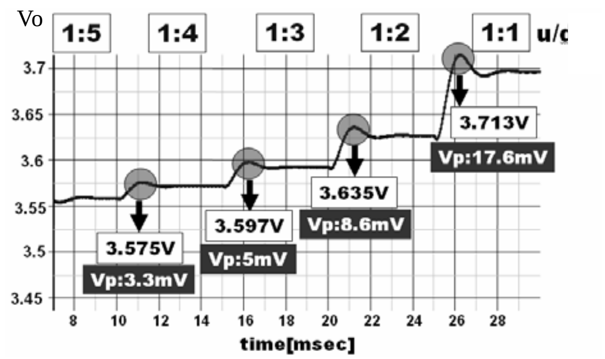

Fig.5. Characteristics of continuous U/D control

Next we consider M:N control of Buck-Boost Converter with D=0.9 fixed. In this circuit the components are L=1.5μH, C=300μF, ESR (Equivalent Series Resistance) =50mΩ and R=5.0Ω (Io=0.5A). The output voltage is stabilized at 2.5V as shown in **Fig.6**. In this figure, the non-controllable area is for Vi between 3.15V and 2.55V, and the voltage drop dVi is about 0.65V in this circuit simulation.

Table 1 Output voltage ripple

Ripple [mV]	M:N	Delta-Sigma
Static(Io=0.5A)		
U/D point	6.3	6.6
dIo (=0.5A)	23	19
dIo (=1.0A)	45	31

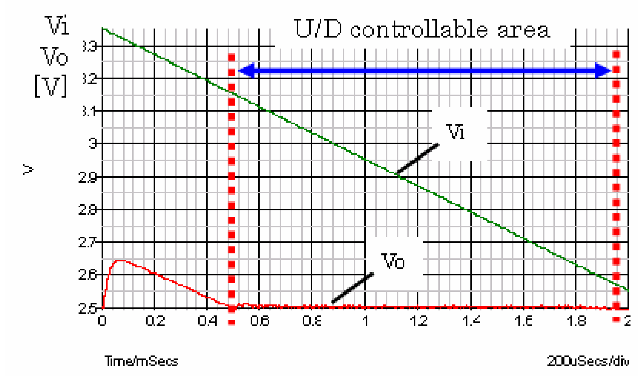

Fig.6. Vo characteristics with U:D control

The ripple is ±6.3mV when toggling between U/D control (at constant load). For load current changes, the ripple is ±23mV at dIo=0.5A and ±45mV at dIo=1.0A as shown in **Table 1**.

4. U/D CONTROL WITH DELTA-SIGMA MODULATION

The use of Delta-Sigma modulation to control the pulse width of PWM signals in DC-DC converters directly has already been investigated. [2)] We use Delta-Sigma modulation in mixed U/D control. **Fig.7** shows a first-order analog Delta-Sigma modulation circuit consisting of an integrator, an adder, an analog-to-digital converter (ADC) and a digital-to-analog converter (DAC). The ADC and DAC have 1-bit resolution, so it is very easy to realize them with a comparator, a latch and an inverter. The output signal of this Delta-Sigma modulator is as shown below:

$$Vo = (u^* \int + n_q)/(1+\int) \qquad (4)$$

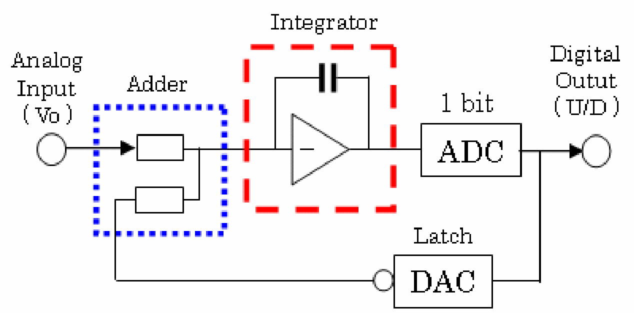

Fig.7. First-order Delta-Sigma modulation

Where u is the input signal and n_q is the quantization noise appearing at ADC.

From (4), the output Vo is a regulated version of input u because the gain of integrator ∫ is very high. On the other hand, the noise shaping transforms low-frequency noise to higher frequencies. The relationship of the output to the input and noise is shown as below.

$$Vo = u + n_q / \int = u + 4 * SIN^2(\pi f / Fs) * n_q \qquad (5)$$

Where Fs is the frequency of ADC sampling, which is synchronized with the PWM signal. Equation (5) shows that the output signal is a regulated version of the input, while low-frequency noise is greatly reduced.

Fig.8 shows the simulated characteristics of the mixed U/D control system using Delta-Sigma modulation. The components of the simulation circuit are an inductor L=1.5 μH, a capacitor C=300μF, ESR=50mΩ and R=5.0Ω. (The output voltage is 3.5V.) The ripple is ±6.6mV when toggling between U/D control (at constant load). For load current changes, the ripple is ±19mV at dIo=0.5A and ±31mV at dIo=1.0A as shown in **Table 1**.

5. CONCLUSION

We have developed a new method of controlling switched Buck/Boost DC-DC converters for mobile equipment. By switching between up-control and down-control and using Delta-Sigma modulation, stable output with small ripple is realized in the "non-controlled" input voltage range. The output voltage ripple is ±6.6mV when toggling between Up/Down control (at constant load) and ±20mV for load current changes of ±0.5A.

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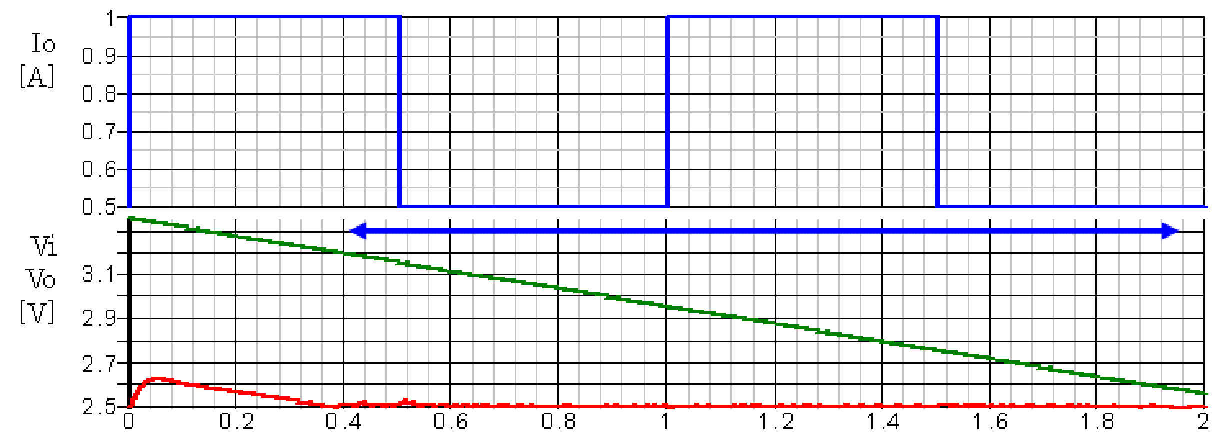

Fig.8. Vo characteristics with Delta-Sigma for dIo (=0.5A)