Mode Transition Improvement by Adding Load Current Sensing Circuit in a Buck-Boost Converter for Mobile Devices

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Abstract - Conventional buck-boost converter by reducing the number of switching has high power efficiency. However, boundary voltage between buck and boost mode shifts as load current changes. This mode shift causes mode transition error. This paper proposes elimination of the error by sensing current flowing through the inductor and making the variable boundary voltage. As results of the circuit simulation, ripple rate is less than ±1.0% and voltage change rate during load fluctuations is less than ±5.0% in the proposed method.

I. Introduction

Many portable devices have become popular in the past few decades. These battery-powered devices, such as laptops and smartphones, provide more and more functions. However, the battery capacity cannot become larger due to the limitation of the battery size. Therefore, the operating time of portable devices significantly decreases with their increasing functions. Hence, it is important for the portable devices to improve power management.

A Lithium-ion (Li-ion) battery is the most popular battery for portable devices. It is small, lightweight and has a large capacity. However, because the output voltage of the Li-ion battery gradually decreases with time (i.e., approximately from 4.2 to 2.7 V), it becomes higher or lower than the required 3.3 V output. This problem is solved by noninverting buck-boost DC-DC converter with a single inductor [1]-[3]. This buck-boost converter consists of one inductor to reduce the area. However, it has four power switches, while a buck or boost converter has only two switches. Because conversion and switching losses increase as the number of power switches increases, it is important to increase the conversion efficiency of the buck-boost converter without increasing the circuit area.

One of the control methods for the buck-boost converter is dividing to three operational modes [1]. In this method, the converter operates in buck, boost and buck-boost mode according to the relationship between its input and output voltages. Its maximum efficiency is 91.6%. However, the efficiency in the buck–boost mode is 34% because the number of switching and the power loss increases. In order to reduce the number of switching, the previous research adds phase to connect the input and output [2]. This method can reduce the number of switching by 75%. However, border voltage which is the center voltage of the buck-boost mode changes with load current. If the border voltage deviates from the appropriate value, the output voltage is changed in the opposite direction. In other words, the output voltage gets away from the target voltage in the buck-boost mode.

This paper proposes the buck-boost converter connecting current sensing circuit in parallel with the inductor. By adding the sensing circuit, the boundary voltage can be changed with respect to changes in current without increasing power loss. The mode transition error can be eliminated by making the variable boundary voltage.

II. Conventional Buck-Boost Converter

A. Principle of Operation

Fig. 1 shows the conventional circuit of the buck-boost converter [2]. It is composed of four power transistors, a mode-select circuit, a ramp generator, an error amplifier (EA), a comparator (CMP) and bandgap and bias circuit. Bandgap and bias circuit generates a reference voltage V_{ref}. EA generates the difference between two inputs of V_{fb} and V_{ref}. CMP compares two inputs of V_{c} and V_{ramp}. CMP switches the output. V_{in} is the input voltage from the Li-ion battery and V_{out} is the output to supply power to the device. This circuit operates four power transistors in pulse width modulation (PWM) control.

Fig. 2 shows mode definition of the mode-select circuit to determine the operation mode. The mode-select circuit in Fig. 1 compares the input voltages with boundary voltages (V_{buck}, V_{bb} and V_{boost}). V_{buck} is the boundary voltage between buck mode and buck-boost mode 1, V_{bb} is the voltage between buck-boost mode 1 and 2, and V_{boost} is the voltage between buck-boost mode 2 and boost mode. For example, when the input is higher than V_{buck}, the mode-select circuit determines the buck mode. When the input voltage is between V_{bb} and V_{boost}. mode-select circuit determines the buck-boost mode 2.

Operation stage of the buck–boost converter has different phases as shown in Fig. 3. Phase 1 is called short phase,

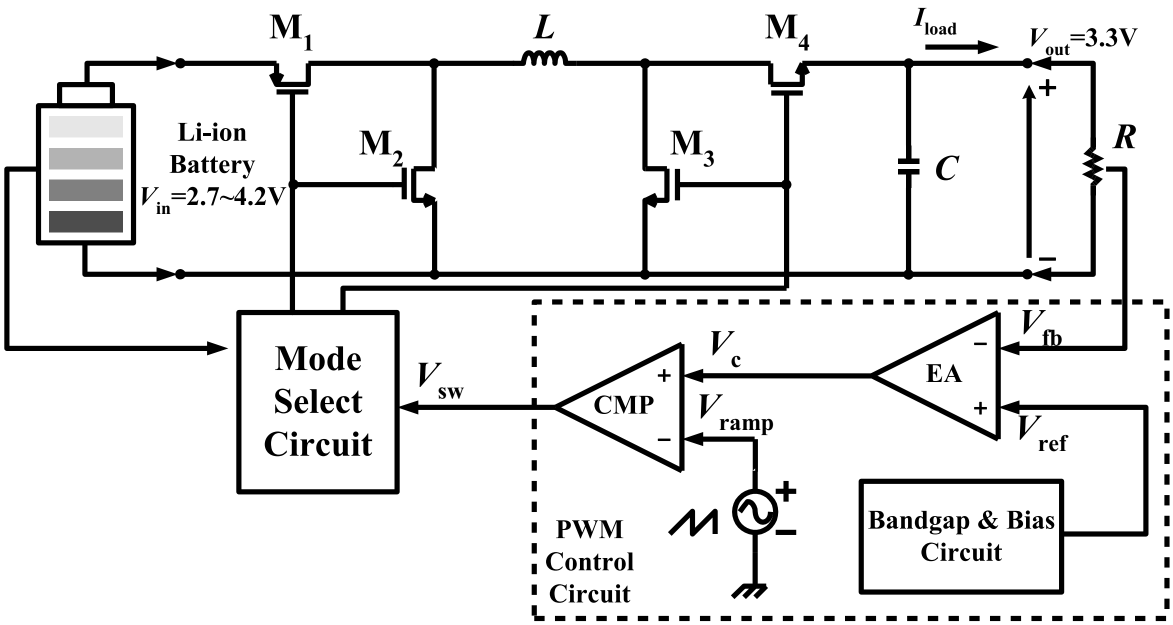

Fig. 1. Conventional buck-boost converter

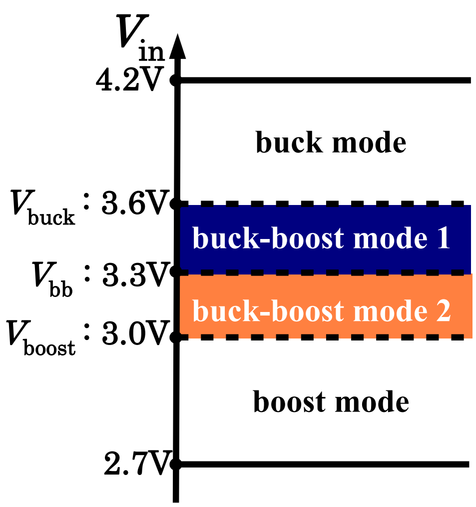

Fig. 2. Mode definition of buck-boost converter

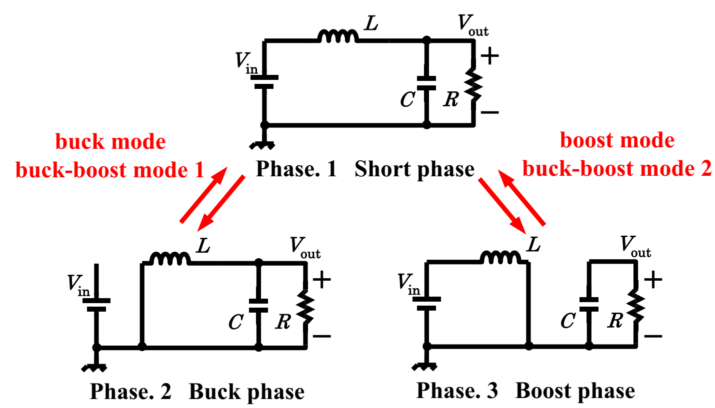

Fig. 3. Three phases of buck-boost converter

which in power transistors M_1 and M_4 are turned ON, and M_2 and M_3 are turned OFF. Phase 2 is called the buck phase, which in power transistors M_2 and M_4 are turned ON, and M_1 and M_3 are turned OFF. Similarly, Phase 3 is the boost phase, which in power transistors M_1 and M_3 are turned ON, and M_2 and M_4 are turned OFF. When the converter operates in the buck mode and the buck-boost mode 1, the operation stage changes between phase 1 and 2. When it operates in the boost mode and the buck-boost mode 2, it changes between phases 1 and 3. However, in the buck-boost mode 1 and 2, phase 1 takes one cycle to stabilize the output voltage at the target voltage while suppressing the number of switching. This operation reduces switching loss and improves power efficiency. Therefore, in buck-boost mode 1, phase 1 → 1 → 2 is repeated one cycle at a time.

B. *Mode Transition Issue*

The boundary voltage V_{bb} is determined by the input voltage in the phase 1. Therefore, the relationship between V_{bb} and the load current I_{load} flowing through L is expressed as

$$V_{bb} = k\, I_{load}\, (\, R_{ON\_M1} + R_{ON\_M4} + R_{DCR}\,), \qquad (1)$$

where k is the coefficient to compare with the input voltage, R_{ON_M1} and R_{ON_M4} are on-resistance of the power transistors M_1 and M_4, R_{DCR} is the inductor winding resistance. V_{bb} depends on I_{load} as expressed in Eq. (1). In other words, V_{bb} changes as I_{load} changes. However, in the conventional method, V_{bb} is set to be constant. As shown in Fig. 4, when I_{load} changes, V_{bb} cannot follow the change and an error occurs. Fig. 4 shows mode transition issue in conventional method. When the error occurs, the output voltage is transformed away from the target voltage.

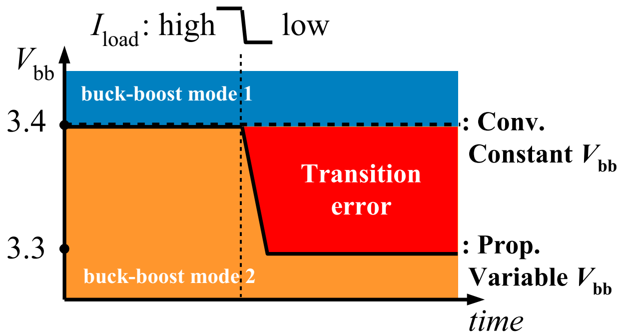

Fig. 4. Mode transition issue

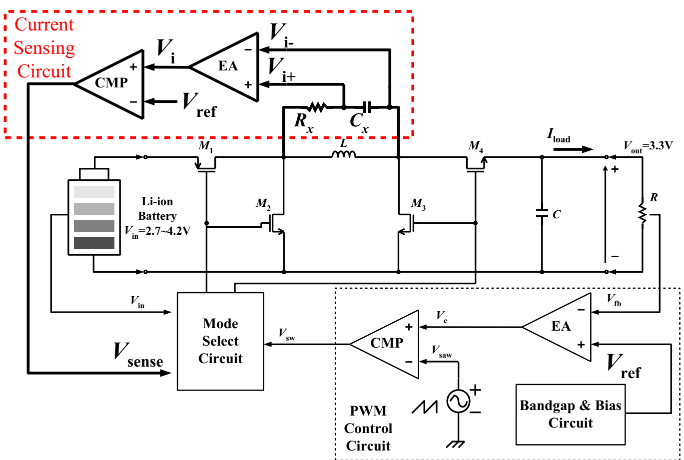

Fig. 5. Proposed buck-boost converter

III. Proposed Buck-Boost Converter

Fig. 5 shows the proposed circuit of the buck-boost converter. Current sensing circuit composed by resistor R_x, capacitor C_x, EA and CMP are added from the conventional circuit. To minimize current flow on R_x, the current sensing circuit must be high input impedance for V_{i+}. In the proposed circuit, current sensing circuit is added in parallel with the inductor L. The current flowing through L is converted to voltage by an additional R_x and C_x. EA detects the voltage across C_x, and outputs V_i. Since V_i changes with I_{load}, the current flowing through L can be sensed.

Fig. 6 shows waveform of V_{sense} and V_i. V_{sense} is generated from CMP by comparing V_i with V_{ref}, which is the output of the bandgap and bias circuit. V_{sense} determines whether V_{bb} is high or low. When V_i is higher than V_{ref}, V_{sense} becomes high. When V_i is lower than V_{ref}, V_{sense} becomes low. In other words, when high load current flows to L, V_{sense} and V_{bb} become higher. Therefore, V_{bb} changes with the changes of I_{load}, and an appropriate boundary voltage is determined.

Fig. 7 shows the proposed mode transition. The conventional mode transition issue can be improved by making variable V_{bb} using current sensing.

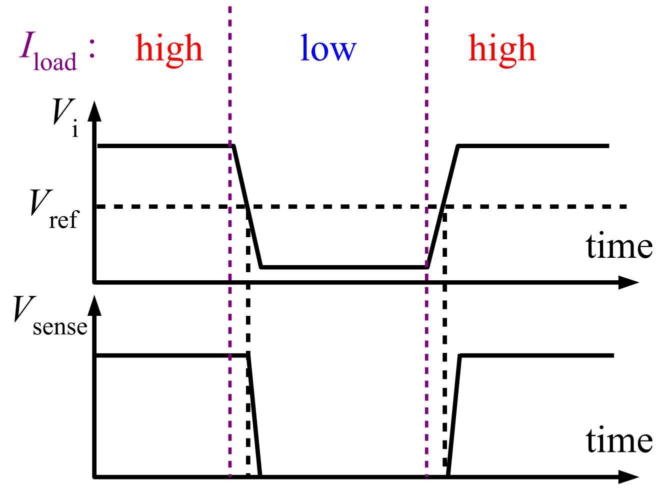

Fig. 6. Waveform of V_{sense} and V_i

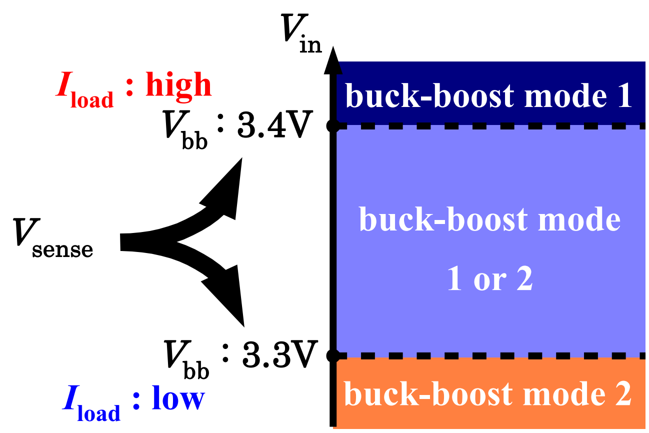

Fig. 7. Proposed mode transition

IV. Simulation

The operation of the proposed buck-boost converter is simulated by LTspice and using ideal switches. Assuming the buck-boost converter for mobile devices, the input voltage is 2.7 to 4.2 V, the target output voltage is set to 3.3 V, and the maximum and minimum load current are 300 mA and 10 mA, respectively. Simulation condition is shown in Table I. Ripple rate, overshoot and undershoot voltage rate in Table I indicate the requirements that the converter must meet. If the converter for mobile devices do not meet these requirements, the device may malfunction due to low operating voltage and is very sensitive to small momentary fluctuations.

Fig. 8 shows simulation results of V_i and V_{ref}. CMP is compared with V_{ref} = 25 mV for V_i. In the simulation, V_{ref} is set as the center voltage of the change of V_i. Fig. 9 shows simulation results of I_{load} and V_{bb} determined by comparing them with CMP. I_{load} is repeated alternately in 10 and 300 mA. V_{bb} is switched to V_{bb} = 3.4 V when I_{load} = 300 mA, and V_{bb} = 3.3 V when I_{load} = 10 mA. Switching V_{bb} in Fig. 9

TABLE I
Simulation condition

Parameters	Value
Input voltage V_{in}	2.7-4.2 V
Output voltage V_{out}	3.3 V
Output current I_{out}	10 or 300 mA
Switching frequency f_{sw}	500 kHz
Inductance L	10 μH
Capacitance C	30 μF
Additional resistance R_x	1.0 kΩ
Additional capacitance C_x	1.0 μF
Ripple rate	± 1.0 %
Overshoot & undershoot voltage rate	± 5.0 %

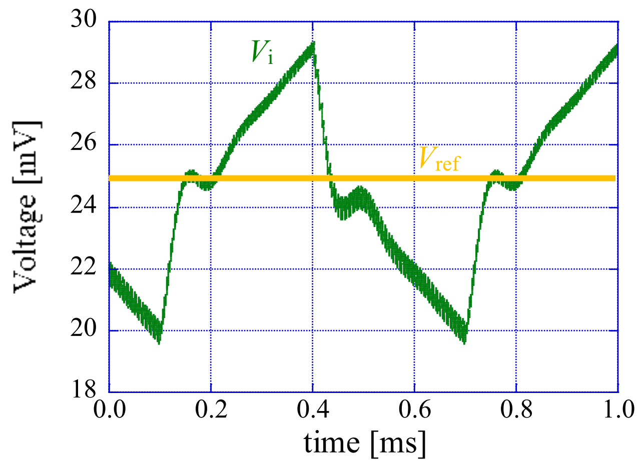

Fig. 8. Simulation results of V_i and V_{ref}

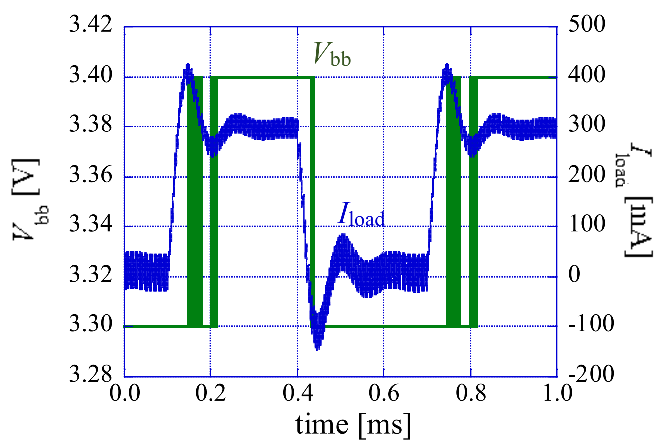

Fig. 9. Simulation result of V_{bb} and I_{load}

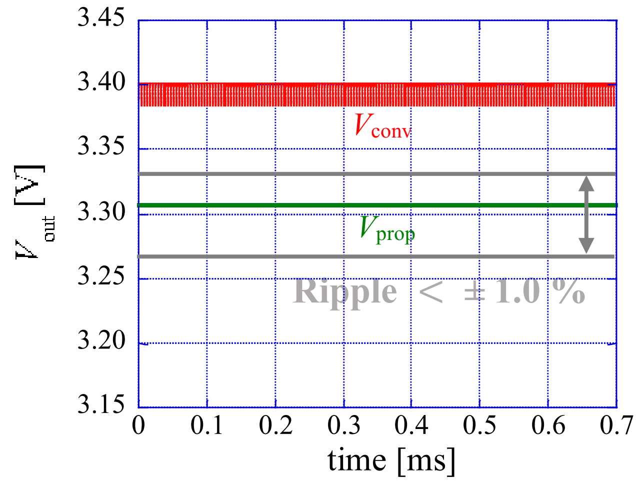

Fig. 10. Simulation result of V_{out} in the conventional and proposed buck-boost converter at V_{in} = 3.35 V

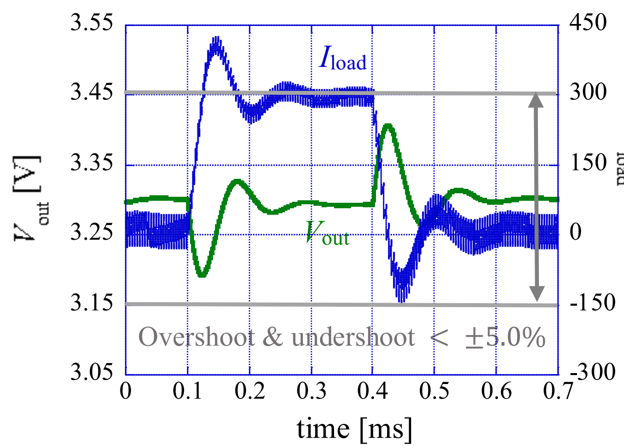

Fig. 11. Simulation results of V_{out} and I_{load}

eliminates the transition error.

Fig. 10 shows the simulation result of output voltage V_{out} in the conventional circuit with the transition error (V_{conv}) and in the proposed circuit (V_{prop}). Although V_{in} is 3.35 V, V_{out} is getting away from the target voltage in the conventional circuit. This is because V_{bb} should be 3.3 V, but it becomes 3.4 V and the transition error occurs. V_{out} has no error and is constant to the target voltage 3.3 V in the proposed circuit. The ripple rate is less than ± 1.0 %.

Fig. 11 shows the simulation result of I_{load} and V_{out} when the load fluctuates in the proposed buck-boost converter. V_{out} maintains overshoot and undershoot less than ± 5.0 % with I_{load} changes.

These simulations are performed with V_{ref} = 25 mV. By changing V_{ref}, the responsiveness of V_{bb} as current change can be improved compared to Fig. 9. However, increasing V_{ref} improves the responsiveness when I_{load} changes from 300 to 10 mA, while becomes worse it when I_{load} changes from 10 to 300 mA. The responsiveness of V_{bb} can be improved by making V_{ref} variable rather than constant.

V. Conclusion

The conventional control method of the buck-boost converter has the problem that the transition error occurs when load current I_{load} changes because the boundary voltage of mode transition is constant. The proposed buck-boost converter adding the current sensing circuit improves mode transition issue and achieved the ripple rate of less than ± 1.0 % and the overshoot and undershoot voltage rate during load fluctuations of less than ± 5.0 %, which are the requirement of converters for mobile devices.

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