Low-Ripple-Voltage and High-Speed Control System for Load Regulation of DC-DC Converter

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ABSTRACT

This paper presents a new approach to creating high-performance control systems for DC-DC converters (switching regulators) targeted for microprocessor and mobile equipment power supply applications. Power supply circuits demand both low-ripple-voltage in the steady state (stability) and fast response for large load changes. However, since in general stability and fast response are trade-off in control systems, it is difficult to satisfy both simultaneously with conventional approaches. We propose a completely different method which uses a variable inductor inside the regulator; the inductor value is automatically varied so that it is large in the steady state to minimize ripple, and small for fast response when the load current changes rapidly. The variable inductor can be realized with parallel or series inductors connected a MOSFET switch. We also propose "soft turn off" technique to adopt the variable inductor inside the DC-DC converter. The load regulation detection circuit (which senses load current change) uses a transformer, a diode-bridge and an operational amplifier. We have performed SPICE simulation, and examined the effectiveness of the proposed methods.

Keywords: *Switching Regulator, Power Supply Circuit, DC-DC Converter, Control System, Variable Inductor*

1. Introduction

Recent electronic devices such as microprocessors and mobile equipment have to operate with low voltage and large current, and they demand DC-DC converters with large current supply capability, low input/output voltage, low ripple, and fast response to sudden load current changes [1]-[8]. In this paper, we approach this DC-DC converter control problem using a variable inductor which may be realized using circuit techniques (such as serial- or parallel-connected inductors and a switch) with soft turn-off mechanism of the switch. We show our basic concepts and simulation results which validate them.

2. Inductor and Control Performance in DC-DC Converter

Fig.1 shows a DC-DC converter (buck converter), where the transient performance in response to large load current change is determined by only the inductor L and the capacitor C regardless of switching frequency or control method. Now we concentrate here on L, and L has to be *small* to reduce the peak overshoot voltage in transient state. However L has to be *large* to reduce the ripple voltage in steady state (when the load current is constant). Thus there is a trade-off for the required value of L regarding to transient performance and steady state performance.

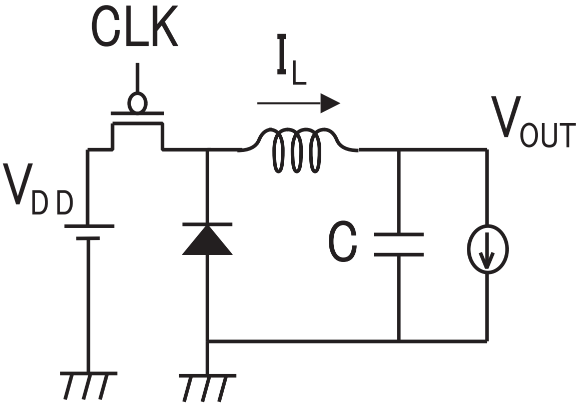

Fig. 1. A switching regulator circuit (buck converter).

In this paper we try to solve this problem using a variable inductor whose value is adjusted automatically to be small in transient state and to be large in steady state. In the following sections, we will de-

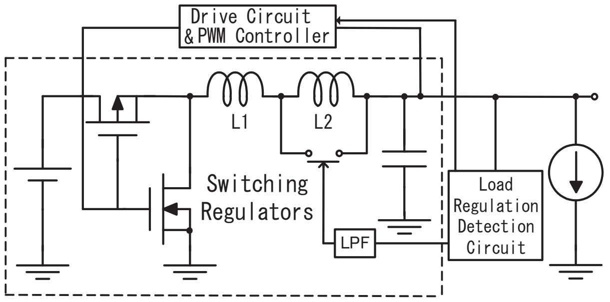

Fig. 2. The proposed circuit with a variable inductor using series inductors and a switch.

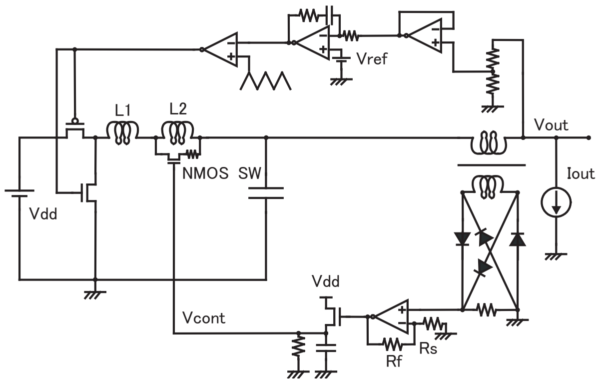

Fig. 3. Whole circuit of the proposed DC-DC converter with a variable inductor, a load current change detection circuit, a LPF and a PWM controller.

scribe how such a variable inductor and automatic adjustment circuit can be realized.

3. Proposed DC-DC Converter Using a Variable Inductor

3.1 Whole Block Diagram of the Proposed Method

Fig.2 shows the block diagram of the proposed DC-DC converter with a variable inductor, while Fig.3 shows its circuit diagram. A variable inductor can be realized with series-connected inductors and a switch as shown in Fig.4, and its operation is as follows:
(1) When the load current is constant, the switch is OFF and the inductor value is $L_1 + L_2$ (which is large) and so output ripple is small.
(2) When the load current changes suddenly (which is sensed by “ load regulation detection circuit ”), the switch turns ON and the effective inductor value is L_1 (which is small) and the DC-DC converter can respond to sudden load changes quickly.

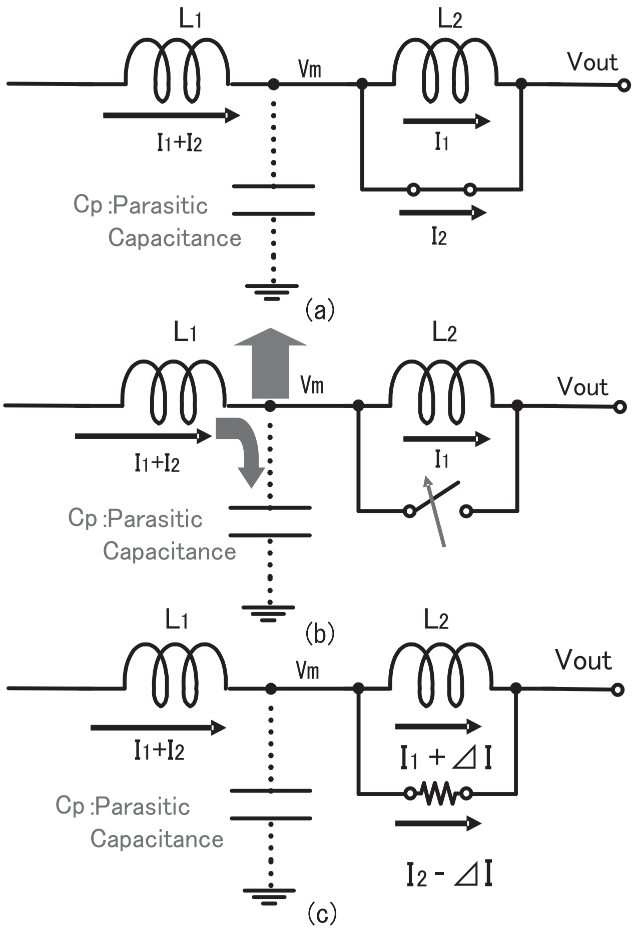

Fig. 4. (a)Two-series-inductors and a switch in ON-stage using the proposed DC-DC converter (Fig.3). (b)In case that the switch turns OFF suddenly, the current I2 flows into the parasitic capacitance which makes its node voltage high. (c)When the switch turns OFF softly, the circuit settles quickly.

3.2 Variable Inductor and Soft Turn-Off

In order to realize the above-mentioned operation, we have to take care of the switch operation in the variable inductor. Fig.4(a) shows the two inductors and the switch which is ON. Current I_1+I_2 flows through L_1, I_1 flows through L_2, and I_2 flows through the switch. If the switch turns OFF suddenly, as shown in Fig.4(b), the current which flows through the inductor cannot change quickly; hence I_2 flows into the parasitic capacitance Cp, and its node voltage may become very high; which is undesirable for fast settling. So, we propose a “ soft turn-off ” switch (meaning that the “ switch ” transitions from ON to OFF gradually). This “ soft turn off ” can be implemented using a low pass filter following the load

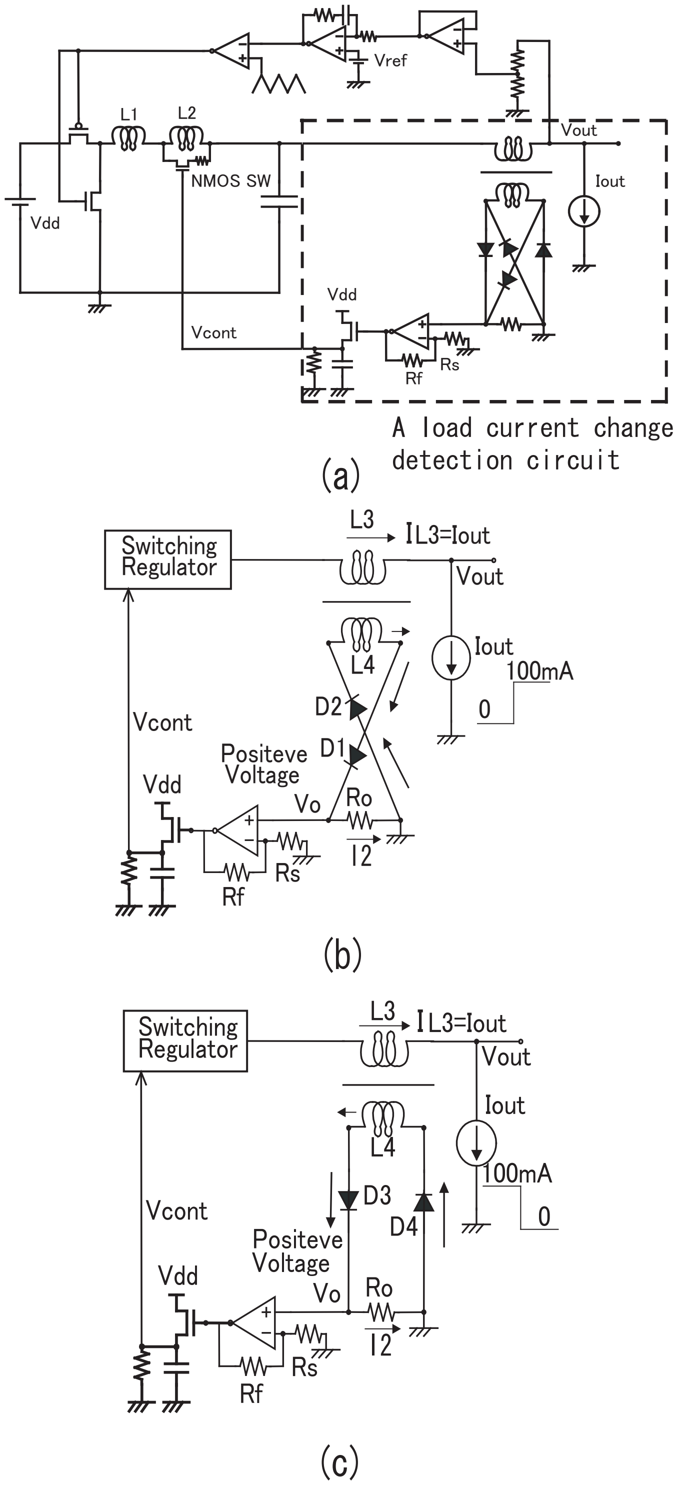

Fig. 5. Load current change detection circuit operation and generation circuit of control voltage V_{cont}. (a) A load current change detection circuit. (b) In case that the load current increases suddenly. (c) In case that it decreases rapidly.

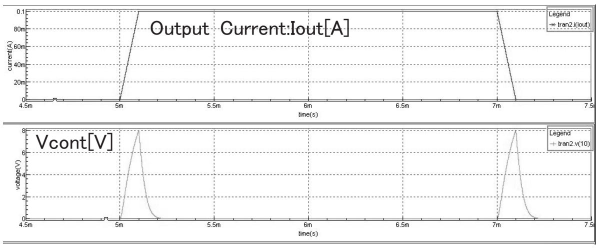

Fig. 6. SPICE simulation results of the load current change detection circuit. Load current (top). V_{cont} voltage (generated control voltage to the switch in the variable inductor) (bottom).

regulation detection circuit in Fig.5: the low pass filter makes the slope of the gate control voltage V_{cont} of the variable inductor switch lower. We also propose a resistor connected to the switch in series as shown in Fig.4(c). When the switch turns off softly, the switch and the resistor have some resistance value in the transient state to prevent current I2 flowing into the parasitic capacitance and creating a high node voltage; we have validated this approach using SPICE simulation.

Note that the variable inductor may also be realized with parallel-connected inductors and a switch.

3.3 Proposed Load Current Change Detection Circuit

Fig.5 shows the load current change detection circuit and V_{cont} generation circuit which controls the switch in the variable inductor. The load current change detection circuit can be realized with a transformer, a diode-bridge, and an operational amplifier. When the load current change is large, its output is logic level 1 (High) and turns ON the switch, while when it is small, its output is logic level 0 (Low) and turns OFF the switch. The operational amplifier follows an RC lowpass filter to realize the soft turn off. Fig.6 shows SPICE simulation results.

4. Simulation Results of Whole Circuit

We first confirm with SPICE simulation that DC-DC converter output ripple is small when the inductor value is large, also that the DC-DC converter responds quickly to load current changes when the inductor value is small. Fig.7 shows SPICE simulation results, which validate the above approach, using fixed inductor values.

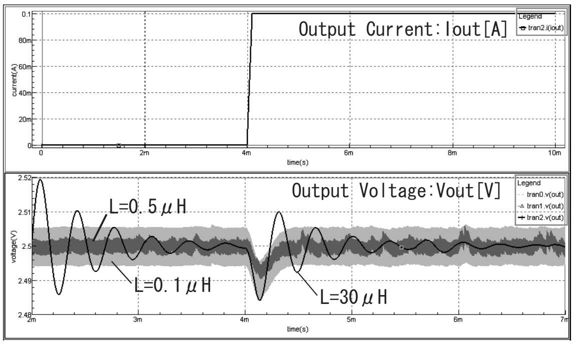

Fig. 7. SPICE simulation results of the DC-DC converter with several L values. Load current (top). Output voltages in response to load current change for fixed inductor values of $0.1\mu H$, $0.5\mu H$, $30\mu H$ (bottom).

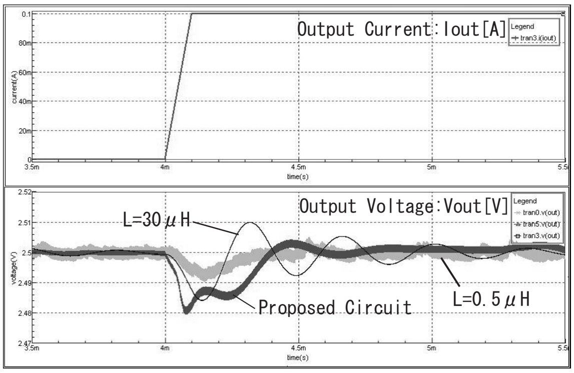

Fig. 8. SPICE simulation result of the proposed DC-DC converter with a variable inductor (Fig.3). Load current (top). Output voltage (bottom).

Next we simulated the proposed circuit in Fig.3, and evaluated it with fixed values of $L = 0.5\mu H, 30\mu H$ as shown in Fig.8. We see that the proposed circuit realizes both low-ripple and fast response. The output ripple may be large in the transient state, but we can increase the clock frequency in this state to reduce this problem. Table 1 summarizes the SPICE simulation results, which validate our proposed approaches.

5. Conclusions

We have proposed control systems for low-ripple, fast-response DC-DC converters using a variable inductor and also considered its implementation using circuit technique. We also propose a soft turn-off technique to adopt the variable inductor in DC-DC converters. Simulation results validate our proposed approach.

Table 1. Simulation results of the proposed approach

	Response time	Ripple voltage
Conventional circuit L=0.5μH fixed	0.6 [ms]	7.0 [mV]
Conventional circuit L=30μH fixed	2.5 [ms]	1.8 [mV]
Proposed circuit variable L	0.9 [ms]	0.5 [mV]

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Appendix: MEMS Design of Variable Inductor and Variable Capacitor

This appendix describes variable inductor and variable capacitor design with MEMS technology. Fig.9 shows variable inductor design with MEMS technology and Fig.10 shows its simulation results. This variable inductor uses spiral inductors with L=216nH, quality factor (Q) =4, and variation ratio of 20%. [8, 9]. Also Fig.11(a) shows the structure of our proposed variable capacitor (which may be also useful for power supply application), and Fig.11(b) shows its simulation results. The capacitance value ranges from 0.1pF to 2.3pF, which is a very high variation ratio (95%). We have used CoventorWare2004 for MEMS variable inductor and capacitor simuation and design. To the best of our knowledge, such variable inductors and variable capacitors have not been used in power supply systems yet, but we consider that they will be useful for future on-chip power supply systems.

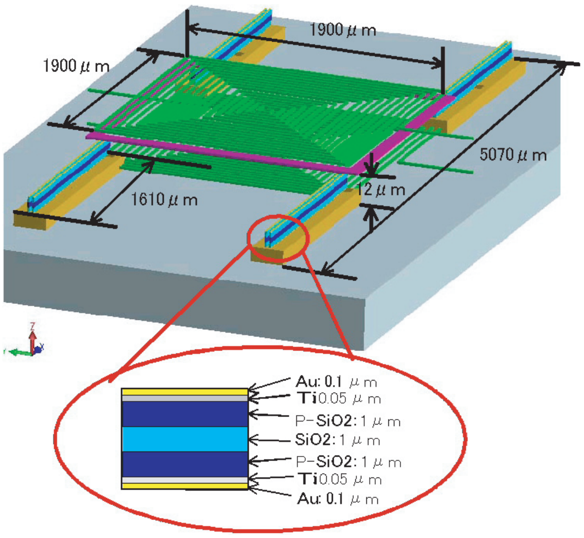


Fig. 9. Proposed structure of an MEMS variable inductor.

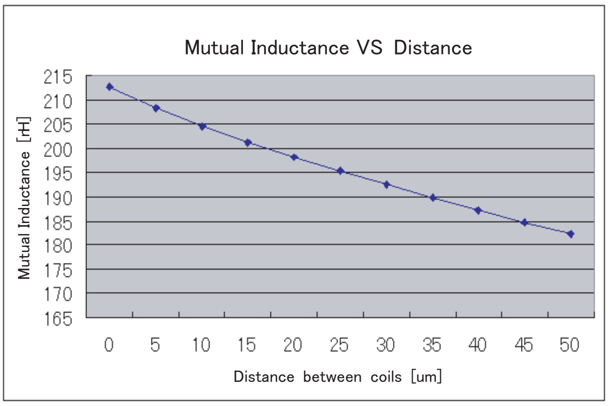
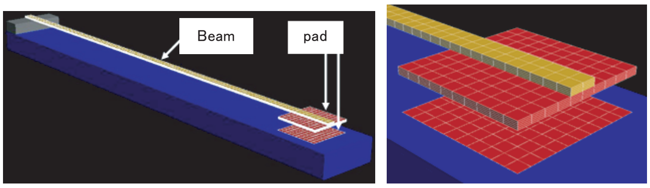
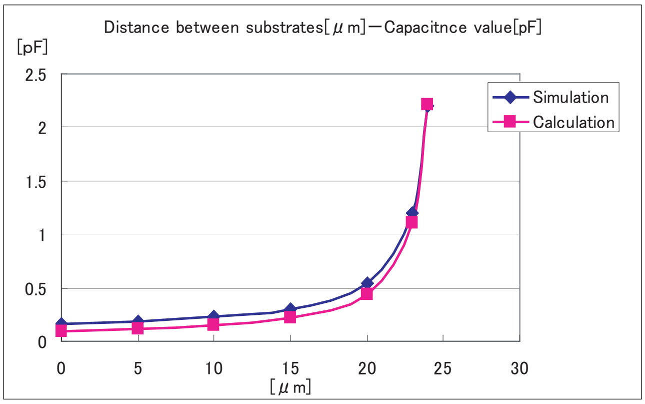


Fig. 10. Simulation result of the MEMS variable inductor in Fig.12.



(a)Proposed structure of an MEMS variable capacitor



(b)Simulation result

Fig. 11. Proposed structure of an MEMS variable capacitor.