Dynamic Characteristics of Pulse Rate Control of a POL Converter

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Abstract - From the perspective of good point-of-load (POL) designs, a fast response for load-change and high power efficiency are important factors. Pulse width modulation (PWM) control is a common control method for POL. Although this control method is very simple and stable for POL, the response for sudden load change is not so fast because of its fixed frequency. However, pulse rate control (PRC) is well suited to such applications. The PRC control method and its features are described, and advantages of PRC are revealed with the some simulated and experimental results.

I. INTRODUCTION

Recently, power management has been introduced to improve the power efficiency of Micro Processing Unit (MPUs), Field Programmable Gate Array (FPGAs) and Digital Signal Processor (DSPs). The power management system includes a full operation mode, standby, and sleep modes. The clock frequency, core voltage and/or core current are changed in each mode accordingly. As a result, the output current of the point-of-load (POL) DC-DC converters is intermittent and has a high slew rate.

A low output voltage, a large output current and a high-speed response, are required for the POL [1].

In such a condition for the control circuit, highly accurate and high-speed control demands that the tolerance of the output voltage becomes internally severe, advanced by speed-up and lowering of the voltage of the MPUs, FPGAs and DSPs [2,3]. A general control method is pulse width modulation (PWM) control. However, for PWM control, the switching frequency is fixed and in this case a delay in the frequency band region results where the change of the load is higher than the switching frequency, especially a delay in the response is caused. In the worst case, the control does not catch up and there exists a possibility that the MPUs, FPGAs and DSPs will stop. In addition, there is a problem in that the ripple of the reactor current increases after the load current increases, as given by the DC bias current characteristics.

This study reveals the problem of PWM control of a POL converter, and proposes the use of pulse rate control (PRC).

PRC consists of a monostable multivibrator and an analog comparator. Switching can be immediately turned on for a change in the load, and a fast-speed response can be achieved. The change of the switching frequency causes suppression of an increase in the ripple of the reactor current.

Firstly, the basic circuitry and problems of PWM control are explained. Then a basic circuitry and the basic principle of operation regarding the PRC method are explained. In addition, the relation between the DC bias current characteristics, the ripple of the reactor current, and the effectiveness of the dynamic characteristic of the PRC method are revealed.

The results of a computer simulation are given regarding the response to a change of output voltage and ripple of the reactor current using circuit simulator Ansoft Simplorer. The experimental results are similarly shown.

II. PWM CONTROL

Fig. 1 shows PWM control of a POL converter, where L is the choke inductor and C_{CO} is the output capacitor. R_{CO} and L_{CO} are the equivalent series resistance and the reactor of C_O, respectively. In basic operation, the gate-pulse of SW_1 and SW_2 is output from a comparator with inputs of a triangular waveform and V_{err}. V_{err} is determined from the output voltage e_o, and a target voltage V_{ref}, through differential amplification with phase compensation.

Fig. 2 shows waveforms at load-change from light load to heavy load. The delay in the response is caused because the switching frequency is fixed for the PWM control method. To achieve a high-speed response for large load changes, speeding-up of the switching speed and addition of phases for multi-phasing are the general methods [4]. However, large switching losses and circuit size become problematic.

The output voltage e_o, is calculated as

$$e_o = \frac{T_{on}}{T_{on} + T_{off}} E_i \qquad (1)$$

where E_i is the input voltage, and T_{on} and T_{off} are on and off terms.

The delay time t_d, shown in Fig. 2, is determined by

$$\frac{(1-D)}{2f_s} < t_d < \frac{(1-D)}{f_s} \qquad (2)$$

where D is the duty ratio and f_s is the switching frequency. From Eq. (2), it is apparent that t_d always exists in PWM control.
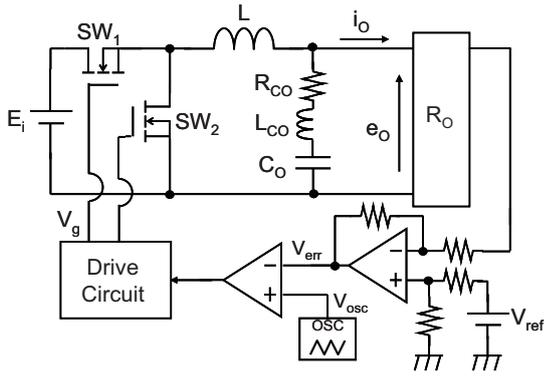
Fig. 1. PWM-controlled POL converter
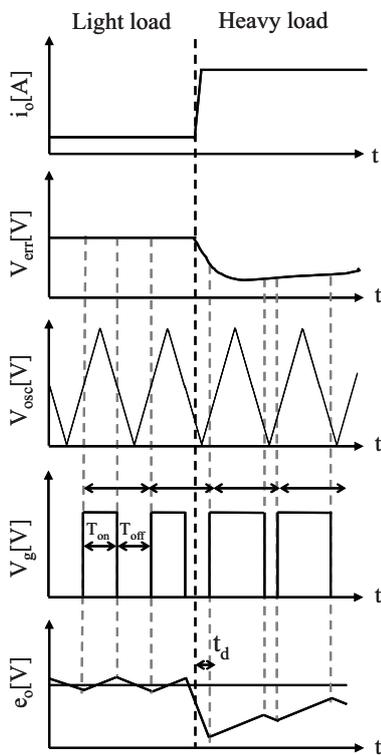
Fig. 2. Load-change from light load to heavy load.

III. PROPOSED CONTROL CIRCUIT

A. Basic Operation

Fig. 3 shows the proposed PRC control circuit for the POL converter, where L is the choke inductor and C_O is the output capacitor. R_{CO} and L_{CO} are equivalent series resistance and reactor of C_O, respectively. The control block is basically composed of a comparator and a monostable multivibrator. V_{ref} is set slightly below a target output voltage E_o.

The comparator outputs a high-level signal just after the e_o dips from V_{ref}. The monostable multivibrator then outputs a pulse signal after receiving the high-level signal. The high-level signal of the monostable multivibrator continues to pre-set the term as a fixed on-term of the high-side switch SW_1. The term between the end of the on-term and the start of the

next high-level output of the comparator is the off-term of the high-side switch SW_1. Therefore, this control method can respond to load changes faster than a PWM response, especially a change from a light load to a heavy load.

T_{on} for PRC is constant, and T_{off} is determined as

$$T_{off} = \frac{2L \cdot \Delta e_o}{\left(\Delta e_o + 2V_{ref}\right) \cdot R_{co}} \quad (3)$$

where Δe_o is the ripple voltage of e_o.

From Eqs. (1) and (3), the following is derived

$$e_o = \frac{T_{on}}{T_{on} + \dfrac{2L \cdot \Delta e_o}{\left(\Delta e_o + 2V_{ref}\right) \cdot R_{co}}} E_i \; . \quad (4)$$
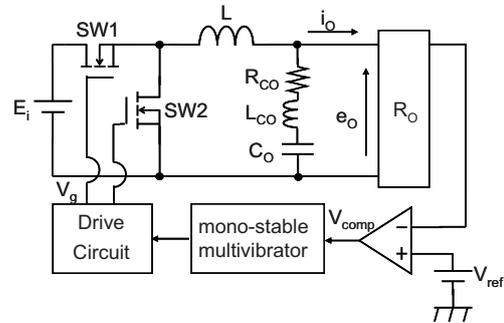
Fig. 3. Proposed PRC POL converter
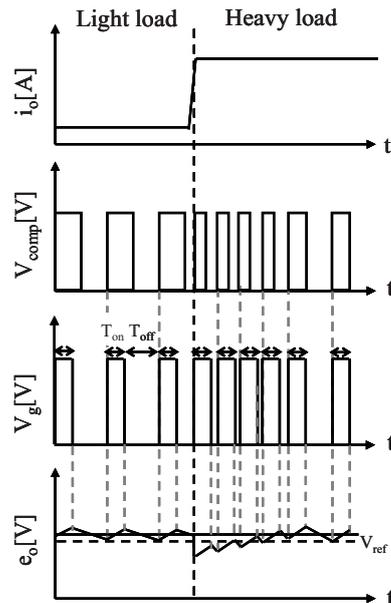
Fig. 4. Load-change from light load to heavy load

B. *Suppression of the Ripple of Reactor Current*

The requirements for a good choke-coil of a power supply circuit are low core-loss, miniaturization, and excellent DC bias current characteristics, etc.

However, these requirements become mutual trade-offs. Miniaturization deteriorates the DC bias current characteristics. This is especially a serious problem for control when the load-change is large, as shown in Fig. 4.

The DC bias current characteristics of a ferrite core are more excellent than those of a dust core. In any case, the inductance changes if the range of the change of direct current broadens.

The ripple of the reactor current Δi_L, is defined as

$$\Delta i_L = \frac{E_o \bullet (E_i - E_o)}{L \bullet f_s \bullet E_i} E_i \tag{5}$$

From Eq. (5), the value of E_i, E_o and f_s are constant for PWM control. When the load current increases, the inductance L is decreased by the DC bias current characteristic shown in Fig. 5. As a result, the ripple of the reactor current is increased.

On the other hand, the switching frequency is not fixed in the PRC method. When the load current increases, the switching frequency increases, too. This is evident from the relation between I_o and f_s.

$$f_s = \left(1 + \frac{R_{co}I_o}{E_o}\right) \bullet \frac{E_o}{E_i} \bullet \frac{1}{T_{on}} \ . \tag{6}$$

Fig. 6 shows the I_o-f_s characteristics under the conditions of T_{on}=0.5 μs, E_o=1.5 V, R_{CO}=0.05 Ω.
Therefore, even if a large load change occurs from a light load to a heavy load, an increase of ripple can be decreased by the switching frequency increase, more than that by PWM control.

As a result, PRC control can improve the problem of DC bias current characteristics. It is also proposed that a low-cost dust core can be adopted as a reactor.
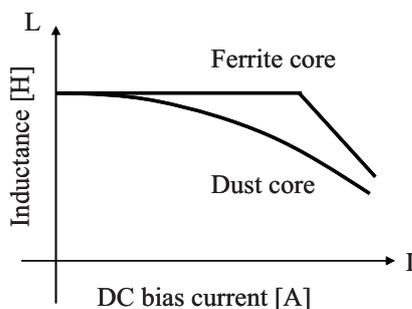
Fig. 5. DC bias current characteristics
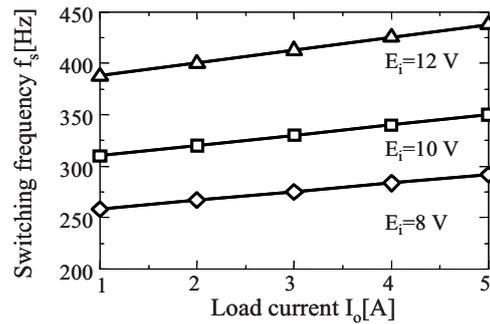
Fig. 6. I_o-f_s characteristics

IV. SIMULATION RESULTS

The computer simulation analysis for PWM and PRC control were performed with a circuit simulator Ansoft Simplorer.
Table 1 and 2 give the parameters and conditions used.

A. *PWM Control*

Fig. 7 shows waveforms for e_o, i_L and v_g at the change point from light load to heavy load.

From the results of PWM control, a response time of 170 μs was confirmed, with an undershoot of 69 mV and an overshoot of 25 mV. The percentage of the output voltage ripple is 1.56%. The ripple of the reactor current is 0.98 A at light load, and 1.02 A at heavy load. Therefore, the ripple of the reactor current increases by approximately 40 mA. The switching frequency is fixed at 500 kHz, and the on-term increases to step up the output voltage in the load change.

Fig. 8 shows waveforms for e_o, i_L and v_g at the change point from heavy load to light load.
From the results of PWM control, a response time of 150 μs was confirmed, with an undershoot of 25 mV, and an overshoot of 70 mV. The switching frequency is fixed at 500 kHz, and the on-term decreases to step down the output voltage in the load change

Table I.
PARAMETERS AND CONDITIONS FOR THE SIMULATION.

Input voltage E_i	12V
Output voltage e_o	1.5V
Switching frequency fs	500kHz
Choke inductor L	2.7μF
Output capacitor C_o	400μF
Equivalent series resistance R_{CO}	20mΩ
Equivalent series reactor L_{CO}	1nH
Load current i_o(light load-heavy load)	1A-3A
Load change slew-rate(SR)	50A/μs

Table II.
CONTROL PARAMETERS. (SIMULATION TIME STEP:0.001μs)

PWM control method	
Proportional gain H_P	10
Integral gain H_I	150000
PRC method	
On-term T_{ON}	0.25μs
Minimum Off-term T_{OFF}	0.75μs
V_{ref}	1.49V
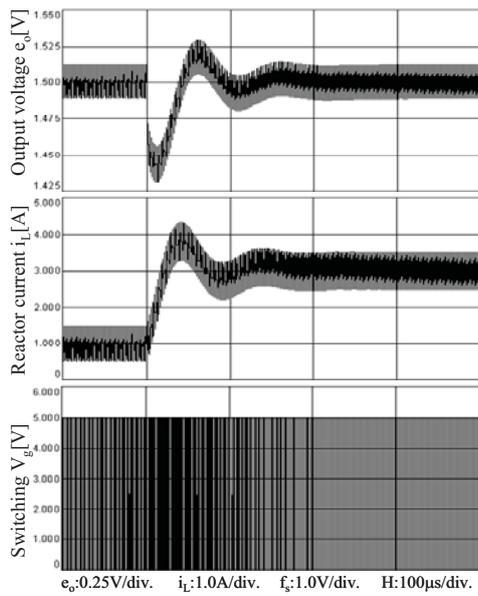
Fig. 7. Load-change simulation results from light load to heavy load (PWM control).
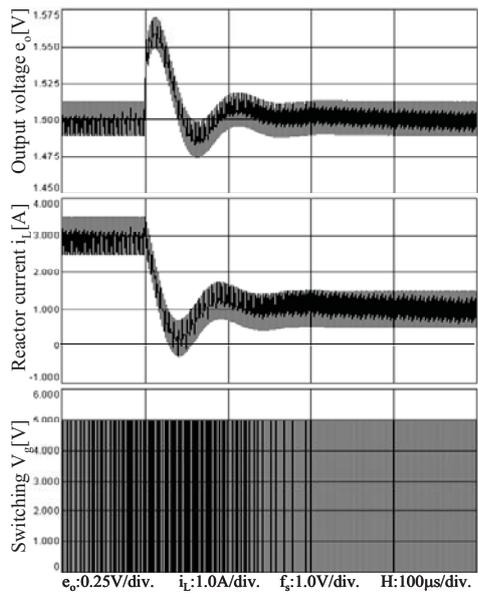
Fig. 8. Load-change simulation results from heavy load to light load (PWM control).

B. Proposed PRC Control

Fig. 9 shows waveforms for e_o, i_L and v_g at the change point from light load to heavy load.

From the results of PRC, a response time of 4 μs was confirmed, with an undershoot of 35 mV. The percentage of the output voltage ripple is 1.53%. The ripple of the reactor current is 0.982 A at light load, and 0.965 A at heavy load. Therefore, the ripple of the reactor current decreases by approximately 17 mA. The switching frequency is 500, 530 kHz and 1 MHz at light load, during transition, and at heavy

load, respectively. When the load current increases, it was confirmed that the switching frequency also increases.

Fig. 10 shows waveforms for e_o, i_L and v_g at the change point from heavy load to light load. From the results of PRC, the response time was confirmed as 5 μs, with an overshoot is 35 mV. The switching waveform was kept off-term during transition, until the output voltage decreased to the target output voltage.
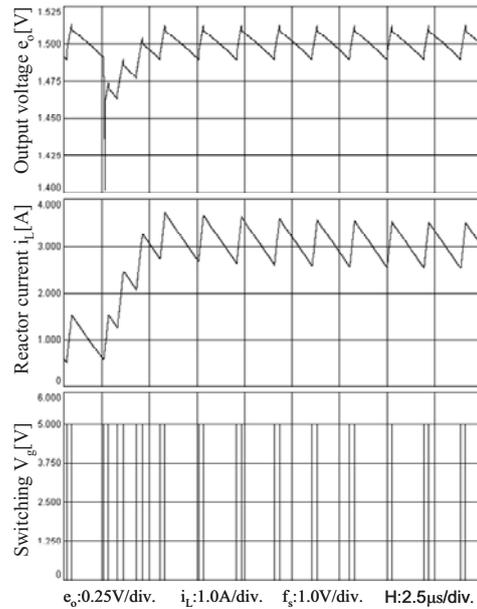
Fig. 9. Load-change simulation results from light load to heavy load (PRC).
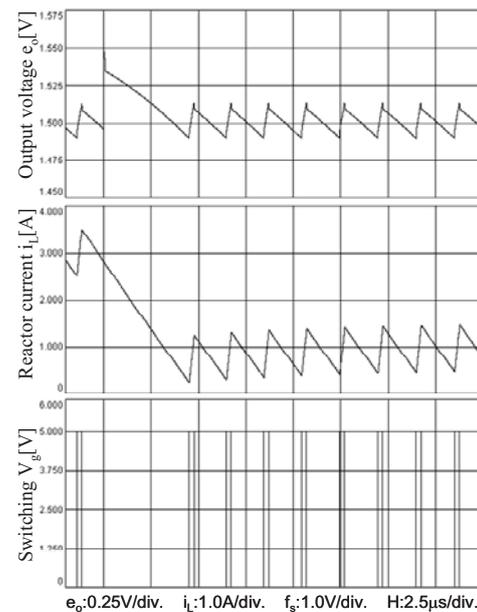
Fig. 10. Load-change simulation results from heavy load to light load (PRC).

V. EXPERIMENTAL RESULTS

A. PWM Control

The experiments were performed using a PWM control-IC (TPS40050, Texas Instruments Co.) [5].

Fig. 11 shows the experimental circuit, and Table 3 gives the experimental conditions.
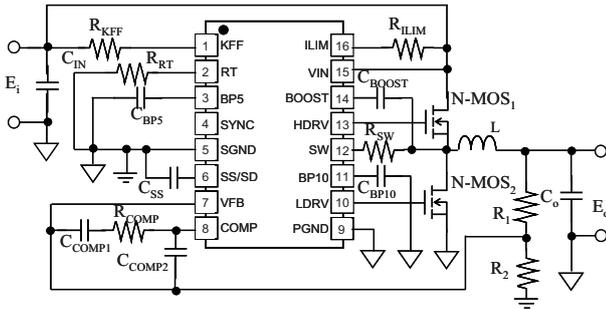
Fig. 11. Experimental circuit (PWM).

Table III.
EXPERIMENTAL CONDITIONS.

Input voltage E_i	8V	Load current i_o (light load-heavy load)	0.6A-1.4A
Output voltage E_o	4V		
Switching frequency f_s	500kHz	Choke inductor L	2.7μF
C_{BOOST}	0.1μF	Output capacitor C_o	330μF
R_{KFF}	30kΩ	Input capacitor C_{in}	20μF
R_{SW}	3.3kΩ	R_1	100kΩ
R_{RT}	90kΩ	R_2	13.2kΩ
R_{ILIM}	3.09kΩ	C_{BP10}	1μF
C_{BP5}	0.1μF	C_{SS}	3300pF
C_{COMP1}	1000pF	C_{COMP2}	82pF
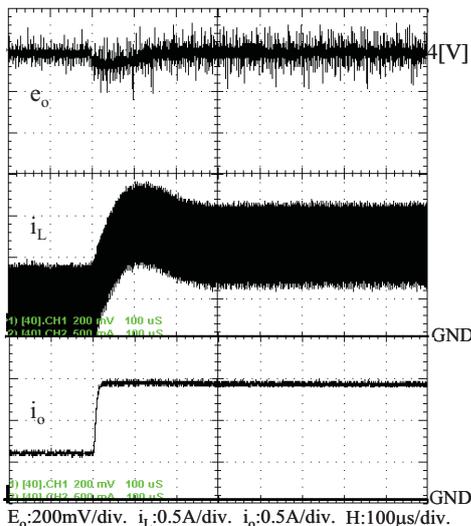
E_o:200mV/div. i_L:0.5A/div. i_o:0.5A/div. H:100μs/div.

Fig 12. Load-change experimental results from light load to heavy load (PWM control).

E_o:200mV/div. i_L:0.5A/div. i_o:0.5A/div. H:100μs/div.
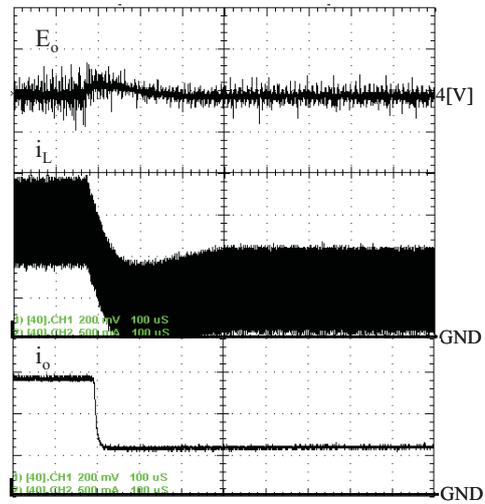
Fig. 13. Load-change experimental results from heavy load to light load (PWM control).

Fig. 12 shows waveforms for e_o, i_L and i_o at the change point from light load to heavy load.

From the results of PWM control, it was confirmed that the response time is 150 μs, with an undershoot of 80 mV. The ripple of the reactor current is 0.95 A at light load, and 0.97 A at heavy load. Therefore, the ripple of the reactor current increases by approximately 20 mA. Also, the noise of the output voltage was greater for the heavy load than for the light load. The switching frequency was fixed at 500 kHz, and the on-term increases to step up the output voltage in the load change.

Fig. 13 shows waveforms for e_o, i_L and i_o at the change point from heavy load to light load.

From the results of PWM control, it was confirmed that the response time is 200 μs, with an overshoot of 60 mV. The switching frequency was fixed at 500 kHz, and the on-term decreases to step down the output voltage in the load change.

B. Proposed PRC

The experiments were performed using a PRC-IC (SI-8405N, Sanken Electric Co., Ltd.) [6].

Fig. 14 shows the experimental circuit, and Table 4 gives the experimental conditions.
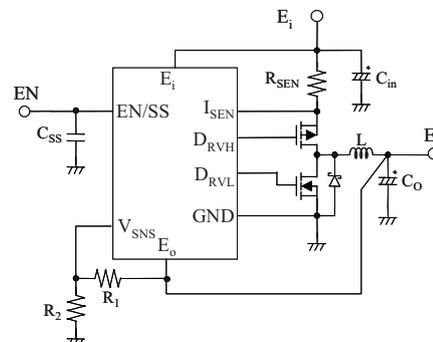
Fig. 14. Experimental circuit (PRC)

Table IV.
EXPERIMENTAL CONDITIONS.

Input voltage E_i	5V	Load current i_o (light load-heavy load)	0A-1.4A
Output voltage E_o	2.5V		
Switching frequency f_s	500kHz	Choke inductor L	2.7µF
On-term T_{ON}	1µs	Output capacitor C_o	330µF
soft-start capacitor C_{ss}	0.022µF	Input capacitor C_{in}	20µF
		MOS Pch/Nch 1PkgSOP8(Toshiba)	
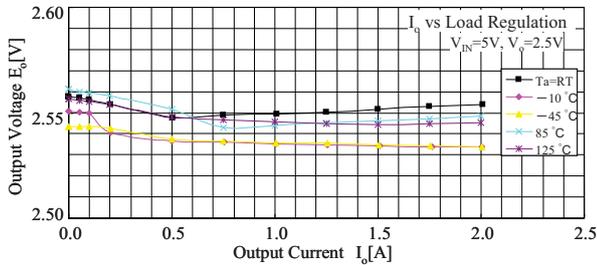
Fig. 15. I_o-E_o characteristic.

Fig. 15 shows the I_o-E_o characteristics for various temperatures.The error is a maximum of 0.02 V for the temperature change. The error rate with a standard voltage is within 2%. Therefore, it was confirmed that highly accurate control is achieved.

Fig. 16 shows waveforms for e_o, i_L and i_o at the change point from light load to heavy load. From the results of PRC, it was confirmed that the response time is 6 µs, with an undershoot of 20 mV. The ripple of the reactor current is 0.77 A at light load, and 0.62 A at heavy load. Therefore, the ripple of the reactor current decreases by approximately 150 mA. The switching frequency is 500, 620 and 830 kHz at light load, during transition and at heavy load, respectively. When the load current increases, it was confirmed that the switching frequency also increases.

Fig. 17 shows waveforms for e_o, i_L and v_g at the change point from heavy load to light load. From the results of PRC, it was confirmed that the response time is 4 µs, with an overshoot of 40 mV. The switching waveform is kept as an off-term during transition, until the output voltage falls to the target output voltage.
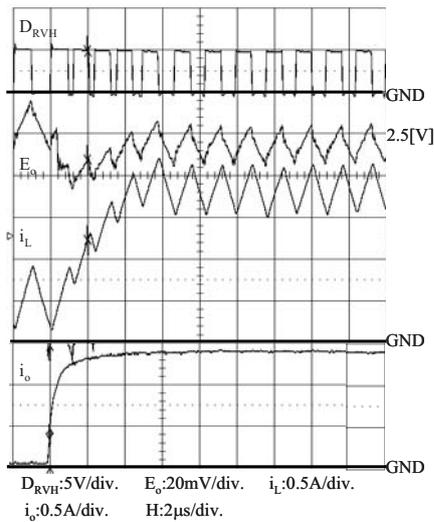
D_{RVH}:5V/div. E_o:20mV/div. i_L:0.5A/div.
i_o:0.5A/div.   H:2µs/div.

Fig. 16. Load-change experimental results from light load to heavy load (PRC).

D_{RVH}:5V/div. E_o:20mV/div. i_L:0.5A/div.
i_o:0.5A/div.   H:2µs/div.
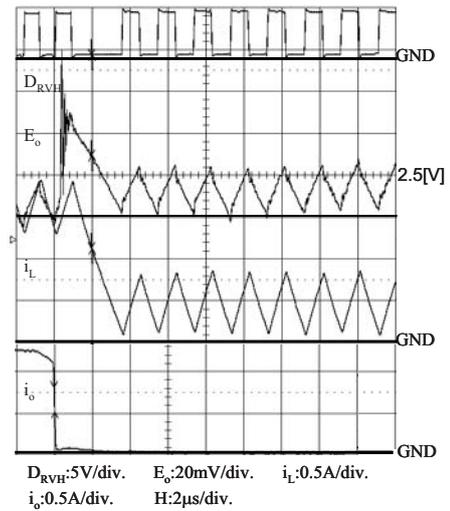
Fig. 17. Load-change experimental results from heavy load to light load (PRC).

VI. CONCLUSION

PWM and PRC control were compared from the aspect of dynamic characteristics using a simulation and experiments. The results gained from PRC suggest that the response time was decreased dramatically. These results indicate that PRC not only allows fast response but also fast convergence. In addition, Δi_L decreased after the load change. This suggests that the increase in the switching frequency cancelled out the influence of the DC bias. The switching frequency was 500, 620 and 830 kHz at light load, during transition and at heavy load, respectively.

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