Performance Characteristics of Digital Current Detector in DC-DC Converter

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***Abstract*— The purpose of this paper is to present a performance characteristics of digital current detector in dc-dc converter. The digital peak current mode control dc-dc converter using the voltage-controlled oscillator (VCO) has already proposed. The peak current is detected by using VCO in the proposed method. The gain of amplifier in the current detector affects to the input voltage range of VCO. Also, it affects the transient response. They are discussed by analysing and simulation.**

Keywords—digital control, peak current mode control, dc-dc converter, digital current detector

I. INTRODUCTION

In the recent year, the amount of information of server in the data center continues to increase. Therefore, the energy management in data center is very important. The digital control dc-dc converter has attracted attention because it has many advantages such as the energy management, the high performance control and the monitoring task [1]-[7]. The digital control circuit is consisted of the A-D converter and the operation derives. The delay time by the conversion time and the operation time exists in the digital control circuit and it adversely affects the transient response of the system. A digital current mode control method is effective for the improvement of the transient response.

However, when the digital peak current mode control is implemented, a high-speed A-D converter, which is expensive, is required in order to capture the peak current value correctly. The digital controller is also required a high-speed processing enough to turn off signal of the PWM at the timing when the current reaches the peak value. Therefore, implementing the peak current mode control by digital technology is difficult.

The authors have already proposed the digital peak current mode control circuit that does not require the high performance equipment [8, 9]. The proposed circuit converts the current value into the FM pulse by using the inexpensive voltage controlled oscillator (VCO). So that, it is possible to capture the peak current using the digital logic circuit, the programmable delay circuit and VCO. The comparison of the conventional method in the transient response has already performed. The analysis of controller of proposed circuit is already derived [10].

This paper presents the transient response in changing characteristics of the current detector. The parameter of the amplifier of the current detector contains the derived control gains. We change the current gain and compare the transient of the output voltage respectively by using the simulation.

II. OPERATION PRINCIPLE

Figure 1 shows the circuit configuration of the digital peak current mode control dc-dc converter. The main circuit is composed of the buck type dc-dc converter. In where, E_i is the input voltage, e_o is the output voltage, R is the load resistance, i_{Tr} is the switching current, R_s is the resistor to detect the switching current, D is the diode, L is the inductance C is the output capacitance i_L is the reactor current T_r is the switch and S_{Tr} is PWM signal. The proposed method uses i_{Tr} instead of i_L to reduce the loss while T_r is off. e_o detected from the main circuit is inputted to the digital control circuit through a preamplifier. The

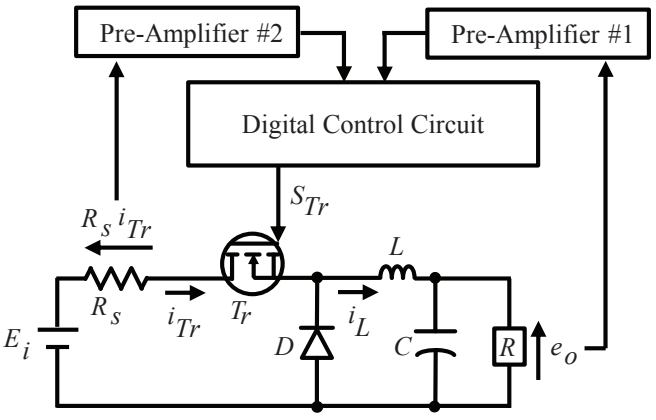

Fig. 1. Circuit configuration of digital peak current mode control dc-dc converter.

voltage $R_s i_{Tr}$ that is equivalent to the switch current detected by the detection resistor is also inputted to the digital control circuit through a preamplifier. S_{Tr} is generated by the digital control circuit using these values.

Figure 2 illustrates the circuit configuration of digital control circuit. e_o is inputted to A-D converter through the preamplifier. A_{eo} is the gain of the preamplifier of e_o. The amplified voltage $A_{eo}e_o$ is converted to the digital value e_o[n] and is inputted to the delay circuit as the calculation results of PID controller N_{PID}. $R_s i_{Tr}$ is inputted to VCO through the preamplifier of $R_s i_{Tr}$. A_{iTr} is the gain of the preamplifier of $R_s i_{Tr}$. VCO is an element, which outputs the pulse frequency modulation (PFM) signal. The output signal S_f of VCO and the signal S_{fd}, that S_f is delayed by a delay

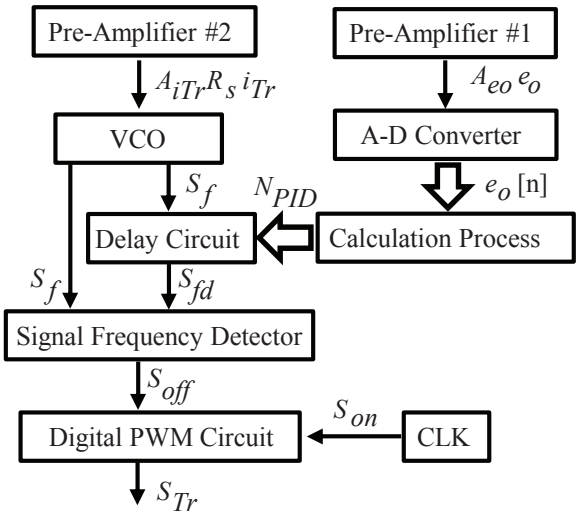

Fig. 2. Circuit configuration of digital control circuit.

circuit, are sent to the signal frequency detector. In the signal frequency detector, the timing of the turn off signal of the PWM is determined by S_f and S_{fd}. The signal of the turn on signal S_{on} of the PWM is sent by the CLK. PWM signal S_{Tr} is determined by this process.

The input-output characteristic of VCO is depicted in Fig. 3. The voltage E_{VCO} is inputted to VCO. E_{VCO}max and E_{VCO}min are the maxim value and minimum value, respectively. E_{VCO} is expressed by (1).

$$E_{VCO} = A_{iTr} R_s i_{Tr}(T_{on}) + E_B \tag{1}$$

where A_{iTr} is the gain of the preamplifier of detected current, $i_{Tr}(T_{on})$ is the switch current in on period and E_B is the bias voltage. VCO outputs the oscillator frequency. The relation of the input voltage and oscillatory frequency is obtained by (2).

$$T_f = \frac{1}{f} = \frac{1}{A_{VCO}\{A_{iTr} R_s i_{Tr}(Ton) + E_B\} + B} \tag{2}$$

where T_f is the one period of S_f, f is the oscillatory frequency, A_{VCO} is the gain of VCO and B is the intercept of VCO characteristic. VCO is the characteristic that outputs the oscillatory frequency proportional to the input voltage. E_{VCO} linearly increases in the proposed method. So, f is gradually increased and T_f is decreased.

Figure 4 shows the timing chart of digital peak current detector. While S_{Tr} is on, i_{Tr} is linearly increased. Therefore, T_f is also gradually shortened. Q_1 is the signal preset by the output voltage control loop and is equal to the delay time τ in the signal frequency detector. τ is obtained by (3).

$$\tau = T_D \cdot N_{PID} \tag{3}$$

where T_D is the resolution of delay buffer per one. The turn

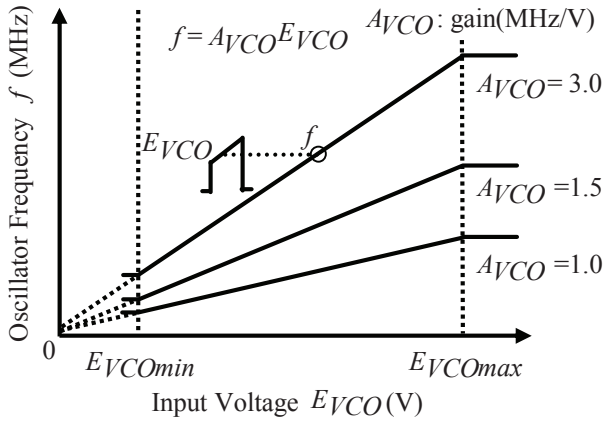

Fig. 3. Input-output characteristic of VCO.

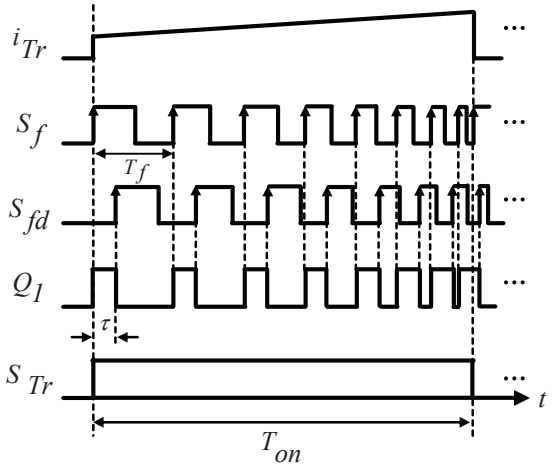

Fig. 4. Timing chart of digital peak current detector.

off of S_{Tr} is determined by the signal frequency detector using S_f and S_{fd}. The following equation is established when the signal frequency detector outputs the turn off signal.

$$\tau = T_f \tag{4}$$

III. Analysis of Control Gains

The control analysis derived by previous research. The peak value of the switch current $i_{Tr}(Ton)$ in the main circuit is obtained by (5).

$$i_{Tr}(Ton) = \frac{V_L}{L} T_{on} + I_L(0) \tag{5}$$

where V_L is the voltage of inductance while the switch is on T_{on} is an on time of the main switch and $I_L(0)$ is the initial value of the inductor current. Here, the relational equation (6) of the current detector and the voltage detector is obtained by using (2), (3) and (4).

$$T_D \cdot N_{PID} = \frac{1}{A_{VCO}\{A_{iTr} R_S i_{Tr}(Ton) + E_B\} + B} \tag{6}$$

$R_S A_{iTr} A_{VCO}$ in (6) is normalized as follows:

$$A_{ICO} = R_S A_{iTr} A_{VCO} \tag{7}$$

A_{ICO} is the current gain. The equation (8) is derived by using (5) and (6). The equation (8) represents the equation of T_{on} by the output voltage detector and the current detector.

$$\frac{\Delta T_{on}(s)}{T_s} = \left\{ H_{PV} + sH_{DV} + \frac{H_{IV}}{s} \right\} \Delta e_o(s) - H_{PI} \Delta I_L(s) \tag{8}$$

H_{PV} is the proportional gain, H_{IV} is the integral gain, H_{DV} is the differential gain and H_{PI} is the current gain in (8). The control gains in (8) derived by previously research are expressed by the following equations.

$$H_{PV} = \frac{2LA_{eo}G_{AD}f_S K_{PV}}{V_L A_{ICO} T_D {N_{PID}}^2} \tag{9}$$

$$H_{IV} = \frac{2LA_{eo}G_{AD}{f_S}^2 K_{IV}}{V_L A_{ICO} T_D {N_{PID}}^2} \tag{10}$$

$$H_{DV} = \frac{2LA_{eo}G_{AD}K_{DV}}{V_L A_{ICO} T_D {N_{PID}}^2} \tag{11}$$

$$H_{PI} = \frac{Lf_s}{V_L} \tag{12}$$

where A_{eo} is the gain of pre-amplifier, G_{AD} is the gain of A-D converter and f_S is the switching frequency. K_{PV}, K_{IV} and K_{DV} are coefficients of the P control, the I control and the D control, respectively.

IV. Simulation Results

Figure 5 illustrates the input-output characteristics of VCO in the simulation. The range of input voltage is varied by changing the value of A_{iTr}. The ranges I, II and III shown in Fig. 5 are A_{ICO} = 5.9 (MHz / A), A_{ICO} = 2.9 (MHz / A) and A_{ICO} = 2.0 (MHz / A), respectively. The transient responses are compared with each range.

Figures 6, 7 and 8 show the result of the transient response of e_o and i_L by using the simulation. The step change of the load resistance is from 10 Ω to 5 Ω. As the main circuit parameter, E_i is 20 V, e_o is 5 V, the switching frequency is 100 kHz, the L is 194 μH, the output capacitance is 990 μF, R_S is 0.05 Ω and R is 5 Ω. K_{PV}, K_{IV}

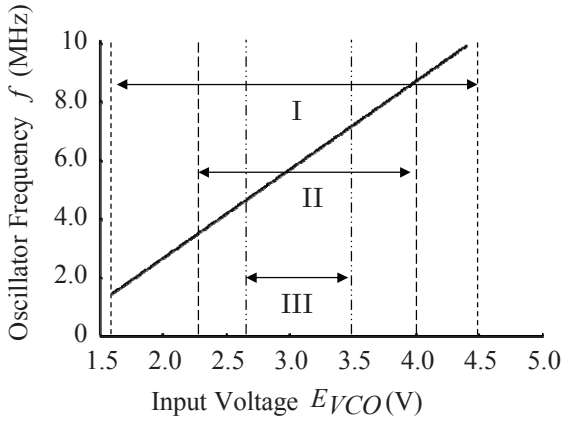

Fig. 5. Input-output characteristic of VCO in simulation.

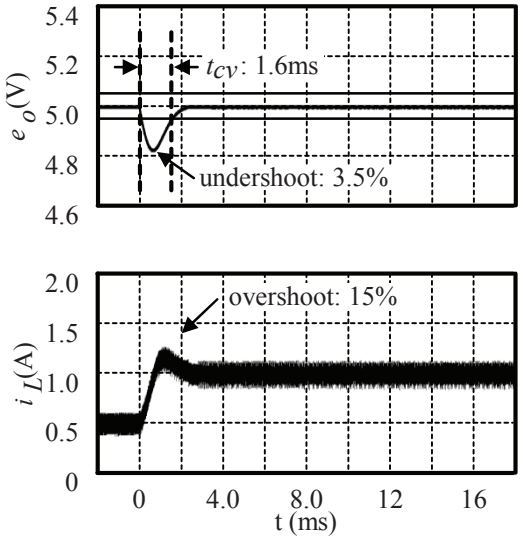

Fig. 6. Transient responses of e_o and i_L taking A_{ICO} = 5.9 (MHz / A) as a parameter.

and K_{DV} are equal to 3, 0.05 and 1, respectively. The difference among Figs. 6, 7 and 8 is the value of A_{ICO}. A_{ICO} is varied by changing the value of A_{iTr} and the value of A_{VCO} is fixed. The value of A_{ICO} is equal to 5.9 (MHz / A) in Fig. 6. The convergence time t_{cv}, the undershoot and the overshoot are 1.6 ms, 3.5% and 15%, respectively. In Fig. 7, the value of A_{ICO} is equal to 2.9 (MHz / A). t_{cv}, the undershoot and the overshoot are 0.8 ms, 1.6% and 8.6%, respectively. Comparing Fig. 7 with Fig. 6, the control gains are doubled. So, t_{cv}, the undershoot and the overshoot are improved by 44%, 46% and 43%, respectively. In Fig. 8, the value of A_{ICO} is equal to 2.0 (MHz / A). t_{cv}, undershoot and overshoot are 0.6 ms, 1.4% and 6.3%, respectively. Comparing Fig. 8 with Fig. 6, the control gains are tripled. t_{cv}, the undershoot and the overshoot are improved by 63%, 60% and 58%, respectively.

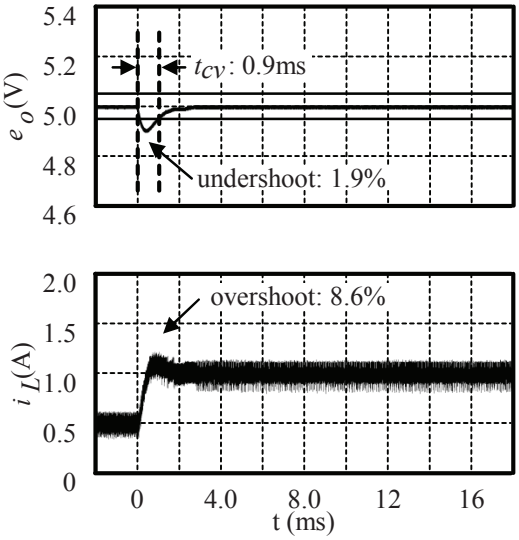

Fig. 7. Transient responses of e_o and i_L taking A_{ICO} = 2.9 (MHz / A) as a parameter.

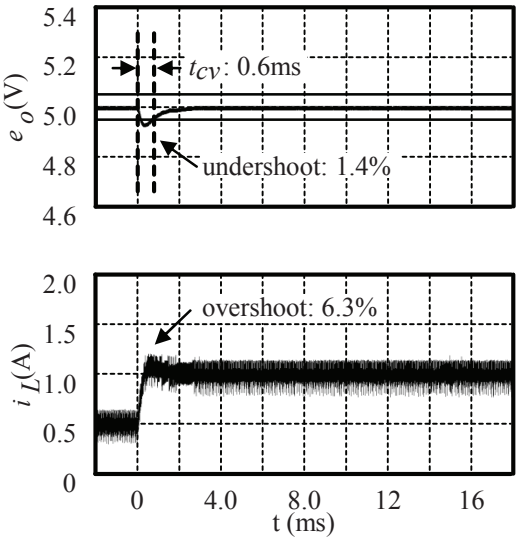

Fig. 8. Transient responses of e_o and i_L taking A_{ICO} = 2.0 (MHz / A) as a parameter.

V. Conclusion

This paper presents the performance characteristics of the current detector in the digital peak current mode dc-dc converter using VCO. The control gains in the proposed method are also derived. It is discussed that the effect of the value of A_{ICO} affects the transient response. A superior transient response is obtained when the value of A_{ICO} is 2.0 (MHz / A) compared with the case of A_{ICO} = 5.9 (MHz / A). t_{cv}, the undershoot and the overshoot are improved by 63%, 60% and 58%, respectively, in Fig. 6 and Fig. 8. When smaller value of A_{ICO} is set, it is possible to obtain a better transient response. Although the transient response is improved by the smaller value of A_{ICO}, the resolution of the current detector is also changed and becomes coarse. Therefore, the proper value should be set to meet both the transient and static characteristics.

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