Digitally Proportional Gain Varying Method for DC-DC Converter

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***Abstract*— The purpose of this paper is to propose a digitally proportional gain varying method for dc-dc converter. In the proposed method, the proportional gain is set to a small value in the steady state and is changed to a large value over stability limit for only a short time in the transient state. Using the proposed method, the transient response can be improved while the dc-dc converter system is kept in stable. Compared with the conventional PID control, the undershoot and the convergence time are improved by 69% and 75%, respectively. Furthermore, the capacitance of output smoothing capacitor must be set to a large value to maintain the stability of system when the control gain is set to a very large value. However, that can be reduced because the very large gain is set for only a short time to improve the transient response in the proposed method. Therefore, the miniaturization of main circuit can be expected.**

Keywords dc-dc converter; digital control; proportional gain

I. Introduction

In recent years, the power consumption has increased by the rapid spread of the IT equipment. For this reason, the saving energy is important and the energy management is required as the function of power supplies. The digital control attracts attention because it is effective to realize such function [1], [2]. Also, the digital control has many advantages: the visualizing the power consumption, the robustness against the aging degradation, the communication with other external component and so forth, which are required as the function of power supplies. Furthermore, the digital control can realize the complex control algorithm and correspond flexibly [3]-[10]. Generally, when the control gain is larger, the transient state is improved. However, the system becomes unstable when this gain is too large. Even if the control gain is within the stable range, this gain should be set to small to suppress the oscillation based on the limit cycle of peculiar to digital control. The authors focus on the flexibility of digital control and then propose the gain switching method to improve the transient response.

This paper presents a digitally proportional gain varying method for dc-dc converter to the improvement of transient response. In the proposed method, the proportional gain is raised to a large value over the stability limit for only a short time and exponentially reduced to the initial value. Moreover, the output smoothing capacitor is enlarged to maintain the stability of the system when the extremely large control gain is set. The proposed method can maintain the stability of system in the steady state because the control gain is small and changes the proportional gain to the large one temporarily to improve the transient response in the transient state.

II. Operation Principle

The block diagram of digital control buck type dc-dc converter is shown in Fig.1. Symbols represent circuit parameters as follows. E_i is an input voltage, and e_o is an output voltage. T_r is a main switch, D is a flywheel diode, L is an energy storage reactor, C is an output smoothing capacitor and R is a load.

Figure 2 illustrates the scheme of digital controller. e_o is sent to the pre-amplifier and fitted to the range of input voltage of A-D converter. The digital value e_o[n] of e_o is sent to the PID controller and the gain changer. The digital value of on time T_{on}[n] is sent to the PWM generator. The PWM generator generates the PWM signal, which is sent to the drive circuit.

Figure 3 describes the mechanism of gain changer. When e_o exceeds the threshold voltage V_{th}, the gain changer suddenly switches the proportional coefficient KP_st for the steady state to the proportional coefficient KP_tr for the transient state to improve the undershoot and the overshoot. This gain changing is performed one times in the start of transient response as shown in Fig.3. KP_tr is set to a larger

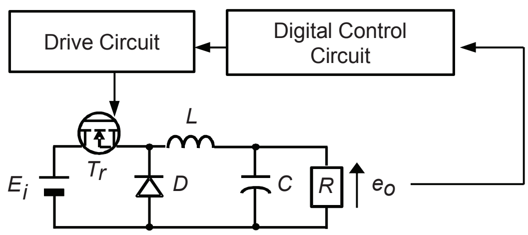


Fig. 1. Block diagram of digital control buck type dc-dc converter.

value than the stability limit of system. Based on the stability criterion of Hurwitz, the stability limit of K_P is equal to about 28 in this system. Also, K_P is attenuated according to following function. In (1), an exponential function is used to attenuate K_P smoothly.

$$K_{p\_st} = K_{P\_tr} e^{-\lambda t} \tag{1}$$

λ is an arbitrary constant that is derived as follows:

$$K_{P\_tr} e^{-\lambda T_{P\_tr}} = K_{P\_st} \quad (t = T_{P\_tr}) \tag{2}$$

$$T_{P\_tr} = T_1 \times 0.5 \tag{3}$$

$$e^{-\lambda T_{P\_tr}} = \frac{K_{P\_st}}{K_{P\_tr}} \tag{4}$$

$$-\lambda T_{P\_tr} = \ln \frac{K_{P\_st}}{K_{P\_tr}} \tag{5}$$

$$\lambda = -\frac{1}{T_{P\_tr}} \ln \frac{K_{P\_st}}{K_{P\_tr}} \tag{6}$$

where T_1 is the time from the start of the transient state to the bottom of the first undershoot in the conventional PID control.

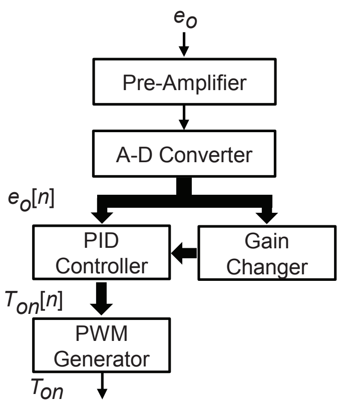


Fig. 2. Scheme of digital controller.

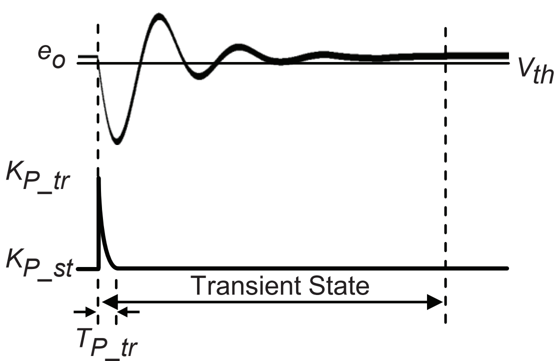
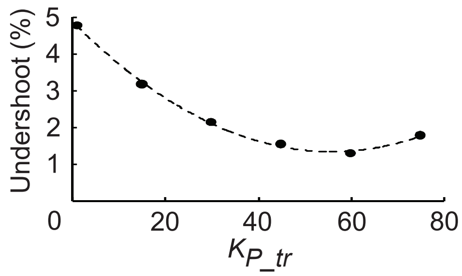


Fig. 3. Mechanism of gain changer.

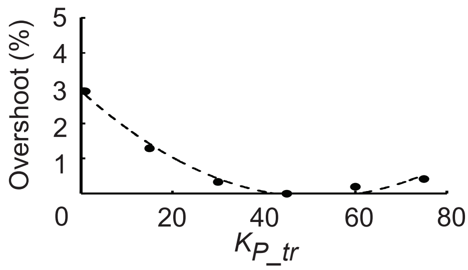
T_{P_tr} is the time when the gain changer works. T_{P_tr} is set to 0.5 times of T_1 not to affect excess range by large K_P. K_P is reduced from K_{P_tr} to K_{P_st} during T_{P_tr}.

III. Simulated Results

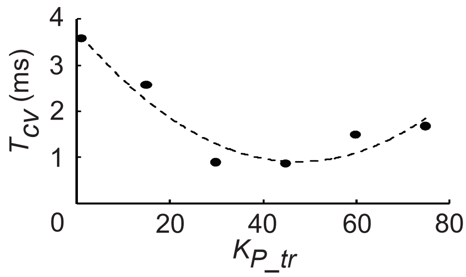
In this section, the transient responses of the conventional PID control and proposed gain switching method are discussed. The simulator is PSIM. The switching frequency f_s is 100 kHz ($T_s = 1/f_s = 10$ μs). As the main circuit parameters: $E_i = 20$ V, $E_o^* = 5$ V, $C = 940$ μF and $L = 189$ μH. The forward voltage drop V_D of diode is 0.3 V. When the main switch is on, the internal resistance r_1 of the dc-dc converter is 0.22 Ω. When the main switch is off, the internal resistance r_2 of the dc-dc converter is 0.22 Ω. The load varies stepwise from 25 Ω to 5 Ω. The resolution of A-D converter is 12 bits. V_{th} is set to 20 mV in order to work the gain changer ideally. The evaluated items are the undershoot, the overshoot and the convergence time T_{cv} of e_o. T_{cv} means the time when e_o converges within



(a) Undershoot.



(b) Overshoot.



(c) T_{cv}.

Fig. 4. The trend of transient characteristics with changing K_{P_tr}.

1% from the desired voltage.

The trend of transient characteristics, which is shown in Fig. 4 is evaluated with changing K_{P_tr}. PID parameters are K_{P_st} is 1, K_I is 0.015, K_D is 1. In this situation, the transient response is improved along with the increase of K_{P_tr}.

Figure 5 depicts the transient response of conventional PID. The undershoot, the overshoot and Tcv are 4.8%, 2.9% and 3.6 ms, respectively. Also, T_1 equals 480 µs. From (3) and (6), λ equals 15861 when K_{P_tr} is 45 and 17990 when K_{P_tr} is 75. Figure 6 illustrates the transient response, the change of K_P and the change of $T_{on}[n]$ of proposed method when K_{P_tr} is 45. K_P is suddenly varied to 45 and $T_{on}[n]$ varies drastically. The undershoot and T_{cv} are 1.5% and 0.9 ms, respectively. Compared with the conventional PID control, the undershoot and T_{cv} are improved by 69% and 75%, respectively. With respect to the overshoot, it is perfectly improved. Figure 7 shows the transient response, the change of K_P and the change of $T_{on}[n]$ of proposed method when K_{P_tr} is 75. K_P is suddenly varied to 75 and $T_{on}[n]$ varies drastically. The undershoot, the overshoot and T_{cv} are 1.8%, 0.4% and 1.6ms, respectively. Compared with the conventional PID control, the undershoot, the overshoot and T_{cv} are improved by 63%, 86% and 52%, respectively. However, when K_{P_tr} is set to 75, the transient response is worse compared with Fig. 6. Therefore, K_{P_tr} should be set properly. In this paper, the optimum K_{P_tr} is determined as 45. Figure 8 illustrates the transient response of conventional PID when K_{P_st} is 45. The system becomes unstable and the output voltage does not converge after the load step because this K_{P_st} is outside the stable range. Figure 9 shows the transient response of conventional PID when K_{P_st} is 4. The undershoot, the overshoot and T_{cv} are 3.2%, 1.5% and 1.6 ms, respectively. Compared with Fig. 5, the

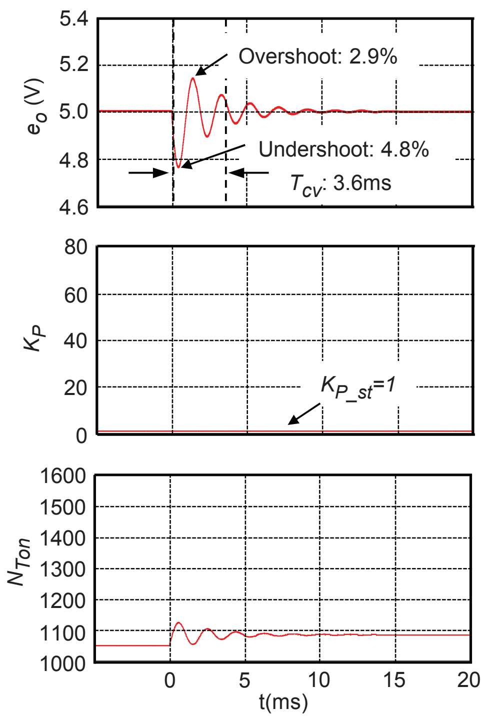


Fig. 5. Transient response of conventional PID control.

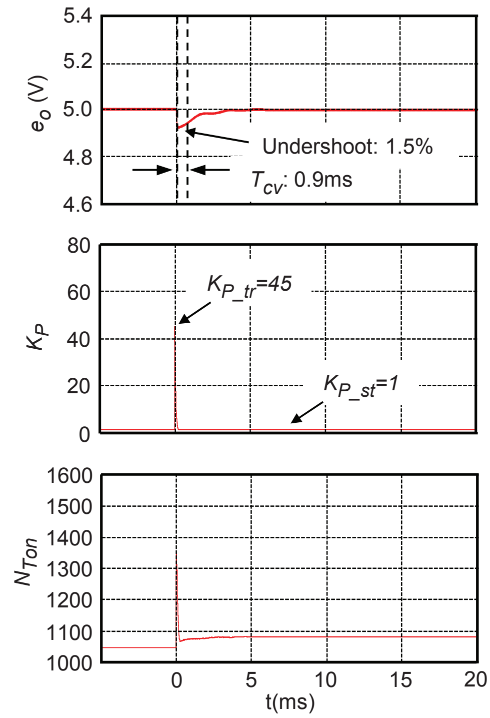


Fig. 6. Transient response of proposed method when K_{P_tr} is 45.

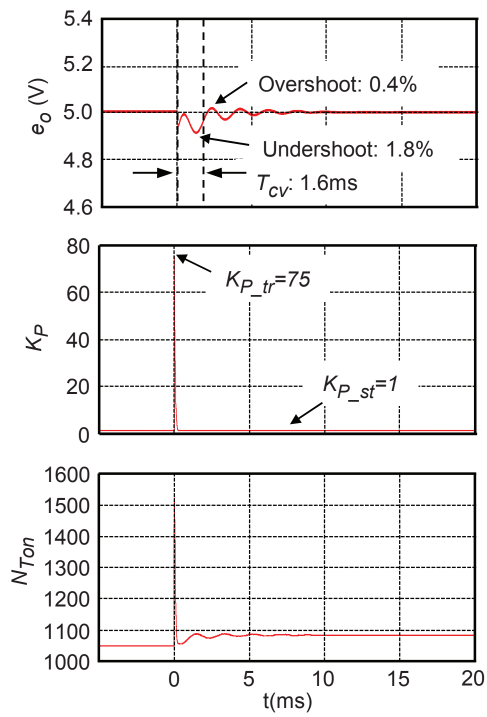


Fig. 7. Transient response of proposed method when K_{P_tr} is 75.

transient response is improved. In this condition, the oscillation based on the limit cycle occurs in steady state before the load step. From Figs. 8 and 9, K_{P_st} should be set to a very small in the conventional PID control. Generally, the capacitance of output smoothing capacitor must be larger when K_{P_st} is set to a large value because the system becomes unstable in the steady state. On the other hand, in the proposed method, K_{P_st} can be set to a very small because K_P changes to very large in transient state. Therefore, the main circuit can be designed in small size by using the proposed method.

Next, T_{P_tr} is considered. It is the period of change of proportional gain K_P. In this section, T_{P_tr} is represented by

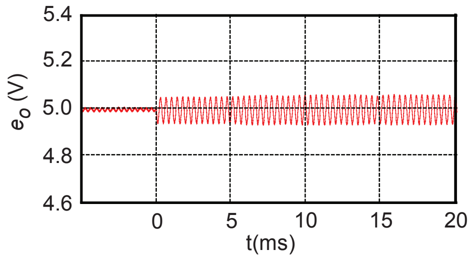


Fig. 8. Transient response of conventional PID control when K_{P_st} is 45.

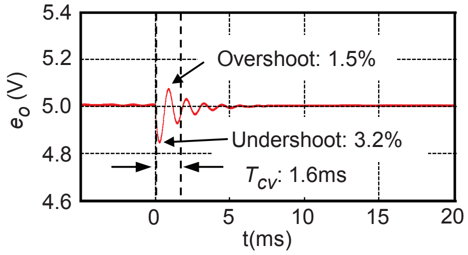


Fig. 9. Transient response of conventional PID control when K_{P_st} is 4.

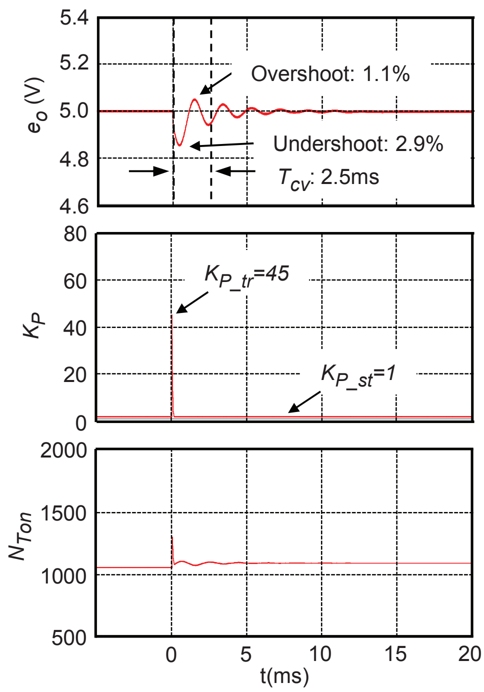


Fig. 10. Transient response of proposed method when α is 0.3.

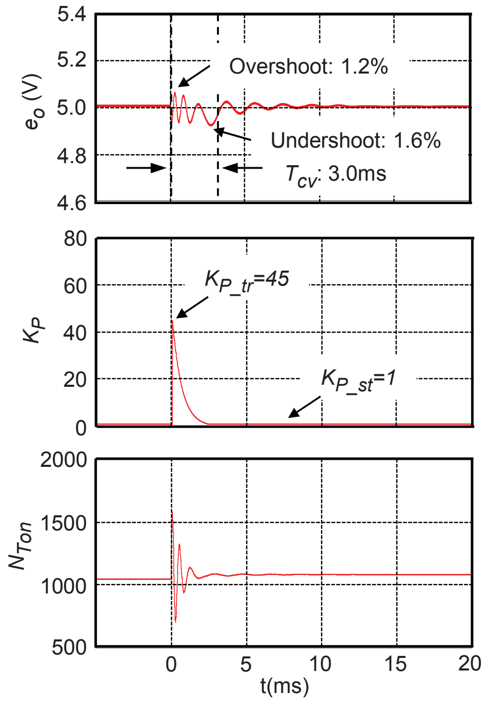


Fig. 11. Transient response of proposed method when α is 5.

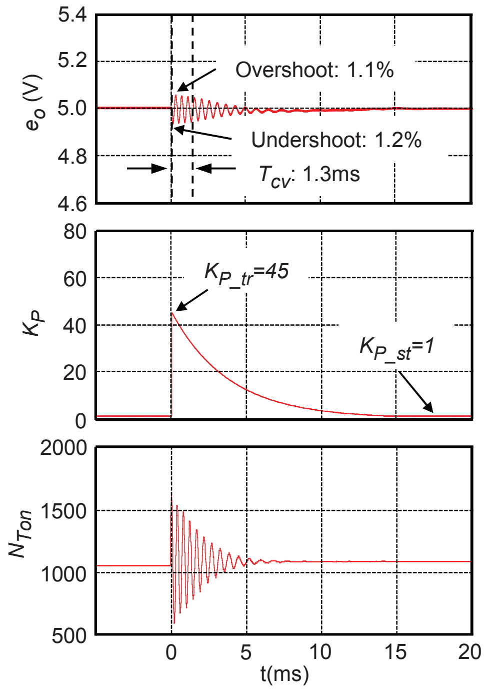


Fig. 12. Transient response of proposed method when α is 30.

following equation.

$$T_{P\_tr} = T_1 \times \alpha \quad (7)$$

where T_{P_tr} is set to α times of T_1. Figures 10, 11 and 12 illustrate the transient response, the change of K_P and the change of $T_{on}[n]$ of proposed method when α is 0.3, 5 and 30. Also, K_{P_tr} is 45. K_P is suddenly varied to 45 and $T_{on}[n]$ varies drastically. Consequently, the transient responses are improved compared with the conventional PID control in Fig. 5 when α is set to 0.3, 0.5, 5 and 30. Meanwhile, when α is too large, the waveform of the output voltage is vibrated. Moreover, the transient response is improved only a little when α is too small. Therefore, α should be set to 0.5 because the best of transient response in α is obtained.

IV. Conclusion

This paper proposed a digitally proportional gain varying method for dc-dc converter. In the proposed method, the proportional gain is set to a small value in the steady state and a large value over the stability limit for only a short time in the transient state. The proportional gain change is realized independently of the stability of the system. As a result, the transient response can be improved by varying the proportional gain to a value over the stability limit temporarily in transient state. When K_{P_tr} is equal to 45, the undershoot and T_{cv} are improved by 69% and 75%, respectively. With respect to the overshoot, it is perfectly improved. Although the capacitance of output smoothing capacitor must be larger when a large K_P is set because the system becomes unstable in the steady state, the capacitance can be reduced and the main circuit can be designed in small size by using the proposed method. Also, T_{P_tr} should be set properly because the waveform of output voltage is vibrated when T_{P_tr} is too long.

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