A New Quick Response Digital Control DC-DC Converter with Dynamic Unstable Gain

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Abstract— **In this paper, we present a new quick response digital control dc-dc converter based on a dynamic unstable gain to improve transient response. In the proposed method, the proportional gain is set to the small value in the steady state and the large value over the stability limit for only a short time in the transient state. Compared with the conventional PID, the undershoot, the overshoot and convergence time are improved by 48%, 71% and 84%, respectively. Generally, when the control gain is set to very large value, the capacitance of output smoothing capacitor must be set to large value simultaneously to maintain the stability of system. That can be reduced and the miniaturization of main circuit can be expected because the very large gain is set for only a short time to improve the transient response in the proposed method.**

Keywords-component; dc-dc converter, digital control, feedback gain

I. INTRODUCTION

Recently, the renewable energy and the energy saving in power supply system are important as the solution to the environmental problems and the depletion of fossil fuel resources. Especially, the energy management is requested to the function of power supplies because the output of the renewable energy is not stable. The digital control is attracting attention because it is effective to realize such function[1],[2]. The digital control dc-dc converter can implement the complex and flexible control algorithm[3]~[10]. On the other hand, the digital control process has the delay time. The A-D conversion time is caused by the A-D converter. Also, processing time is caused by the digital controller such as field programmable gate array (FPGA) and digital signal processor (DSP). The delay time adversely affects the transient response.

This paper presents a new quick response digital control dc-dc converter based on a dynamic unstable gain to improve the 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. Generally, the control gain should be set considering both steady and transient state. 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. Also, the proposed method can switch the proportional gain to the value over the stability limit to improve the transient response in the transient state. The capacitance of output smoothing capacitor typically must be large because the system becomes unstable during the steady state when the large gain is kept. The proposed method can avoid it and realize the improvement of transient response. In addition, the input voltage of dc-dc converter is likely to fluctuate because the output of natural energy to such as the solar power and the wind power is unstable. However, the proposed method can similarly improve the transient response if the fluctuation of the input voltage occurs.

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. D is a flywheel diode, T_r is a main switch,, R is a load, C is an output smoothing capacitor and L is an energy storage reactor.

Figure 2 illustrates the scheme of digital controller. e_O is sent to the A-D converter through the pre-amplifier and is converted to the digital value e_O[n]. e_O[n] is processed in the gain changer and the PID controller. The digital value of on time T_{on}[n] is sent to the PWM generator. The PWM

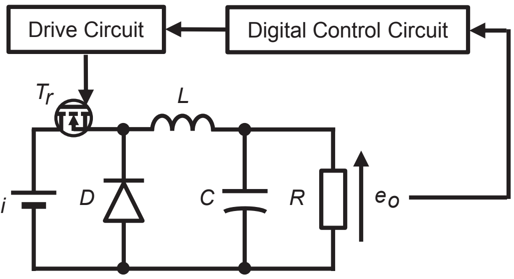

Figure 1. Block diagram of digital control buck type dc-dc converter.

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generator produces the PWM signal which is taken to the drive circuit.

Figure 3 illustrates the mechanism of gain changer. The gain changer changes proportional coefficient K_{P_st} to K_{P_tr} suddenly to improve the undershoot and the overshoot when e_O exceeds the threshold voltage V_{th1}or V_{th2}. This gain changing is performed three times in the start of transient response as shown in Fig.3. K_{P_tr} is set to larger value than the stability limit of system. Based on Routh-Hurwitz stability criterion, the limit of stability in K_P is obtained 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 which is derived as follows:

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

$$T_{P\_tr} = T_1 \times 0.75 \tag{3}$$

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

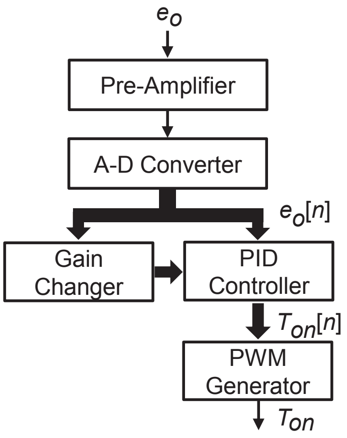

Figure 2. Scheme of digital controller.

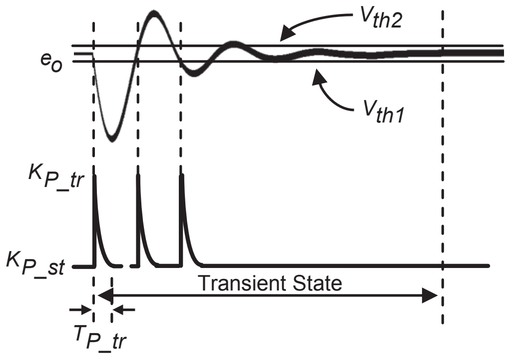

Figure 3. Mechanism of gain changer.

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

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

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. T_{P_tr} is the time when the gain changer works. T_{P_tr} is set to 0.75 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 conventional PID control and the proposed gain changing method in the transient state under the stepwise load variation from 25 Ω to 5 Ω are argued. The simulator is PSIM. The switching frequency f_s is 100 kHz ($Ts=1/fs=10$ μs). As the main circuit parameters: E_i=20 V, E_O*=5 V, C=470 μF, L=200 μH. The forward voltage drop V_D of diode is 0.25V. The internal resistance r_1 in the dc-dc converter is 0.153 Ω when the main switch is turned on. Also, the internal resistance r_2 in the dc-dc converter is 0.266 Ω when the main switch is turned off. The resolution of A-D converter is 11 bits. The evaluated items are as follows: the undershoot, the overshoot and convergence time T_{cv} of e_O. T_{cv} means the time when e_O converges within 1% from the

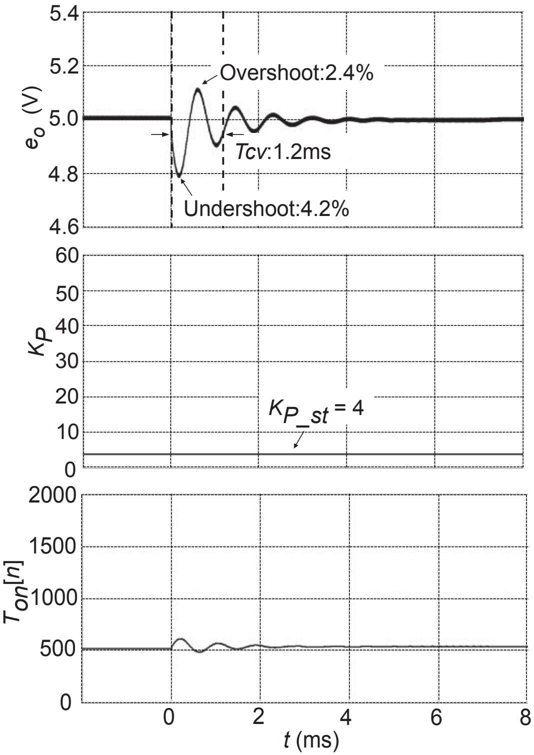

Figure 4. Waveform of e_O, K_P and T_{on}[n] of conventional PID control in transient state (E_i = 20 V).

desired voltage.

At first, Fig. 4. shows the waveform of e_o, K_P and T_{on}[n] of conventional PID control in transient state. The undershoot, the overshoot and T_{cv} are 4.2%, 2.4% and 1.2ms, respectively. Also, T_1 equals 230 μs. From (3) and (6), λ equals 11681 when K_{P_tr} is 30 and 19717 when K_{P_tr} is 120. Figure 5 depicts the waveform of e_o, K_P and T_{on}[n] of proposed method in transient state when K_{P_st} and K_{P_tr} are equal to 4 and 30. K_P is changed from 4 to 30 temporarily and T_{on}[n] becomes large drastically. The undershoot, the overshoot and T_{cv} are 2.2%, 0.7% and 0.2 ms, respectively. The transient response is improved by changing the proportional gain. In concrete, the undershoot, overshoot and T_{cv} are improved by 48%, 71% and 84%, respectively. Figure 6 illustrates the waveform of e_o, K_P and T_{on}[n] of proposed method in transient state when K_{P_st} and K_{P_tr} are equal to 4 and 120. The undershoot, the overshoot and T_{cv} are 4.1%, 4.5% and 2.0ms, respectively. K_P is changed from 4 to 120 temporarily and T_{on}[n] becomes large drastically as with Fig. 5. However, the proportional gain varying method affects excessively and brings the worsening of transient response. Thus, K_{P_tr} should be set properly.

Figures 7 and 9 show the waveform of e_o, K_P and T_{on}[n] of conventional PID control in transient state when E_i is equal to 16 and 24. Also, Figs. 8 and 10 illustrate the waveform of e_o, K_P and T_{on}[n] of proposed method in transient state when

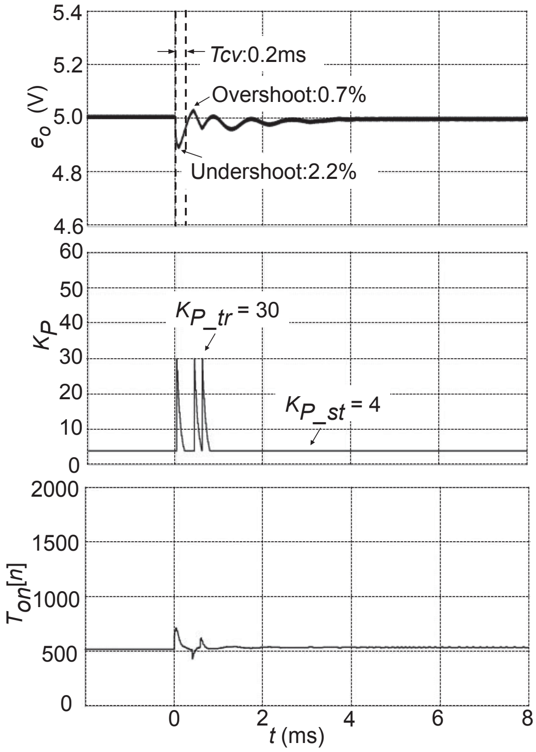

Figure 5. Waveform of e_o, K_P and T_{on}[n] of proposed method in transient state when K_P is changed from 4 to 30 (E_i = 20 V).

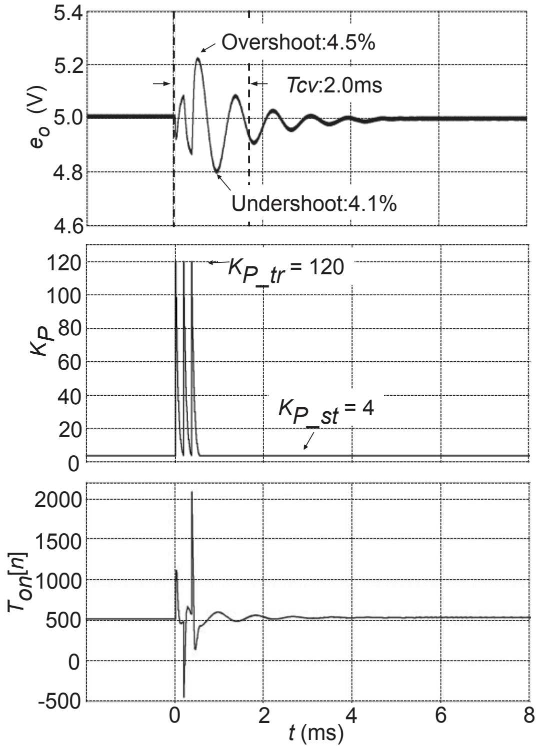

Figure 6. Waveform of e_o, K_P and T_{on}[n] of proposed method in transient state of proposed method when K_P is changed from 4 to 120 (E_i = 20 V).

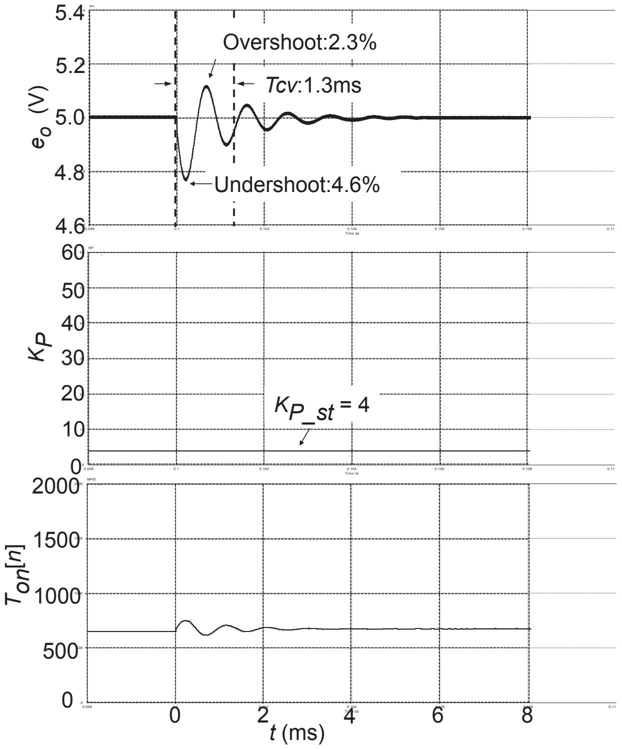

Figure 7. Waveform of e_o, K_P and T_{on}[n] of conventional PID control in transient state (E_i = 16 V).

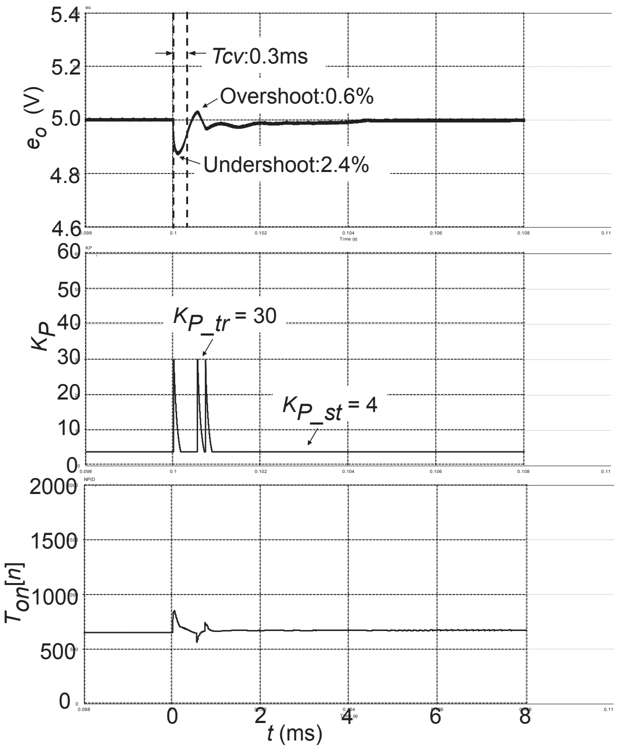

Figure 8. Waveform of e_O, K_P and T_{on}[n] of proposed method in transient state when K_P is changed from 4 to 30 (E_i = 16 V).

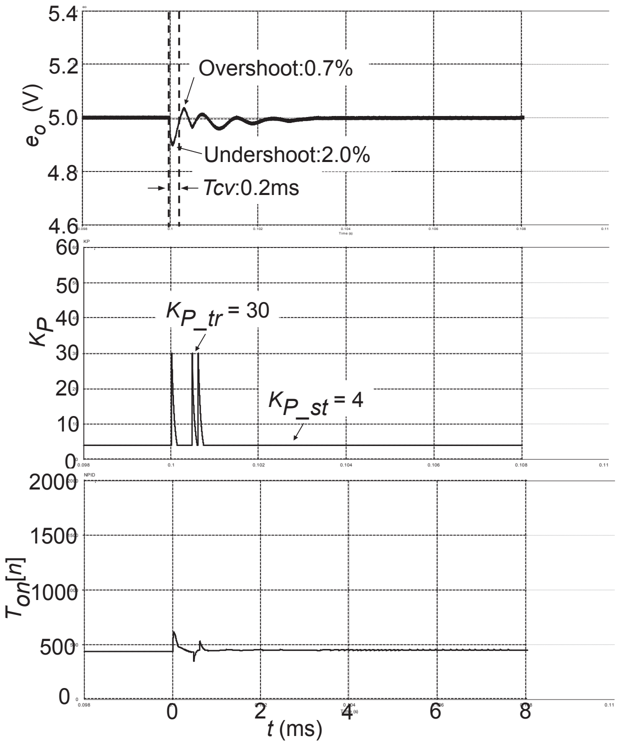

Figure 10. Waveform of e_O, K_P and T_{on}[n] of proposed method in transient state when K_P is changed from 4 to 30 (E_i = 24 V).

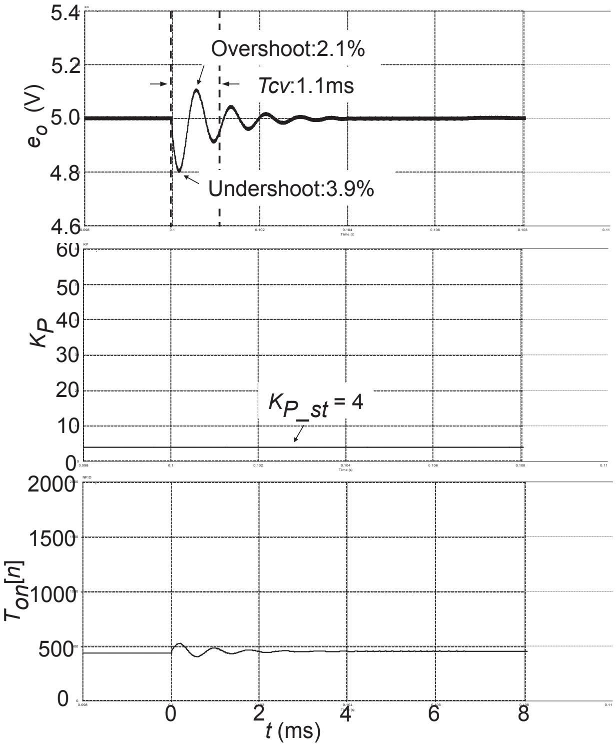

Figure 9. Waveform of e_O, K_P and T_{on}[n] of conventional PID control in transient state (E_i = 24 V).

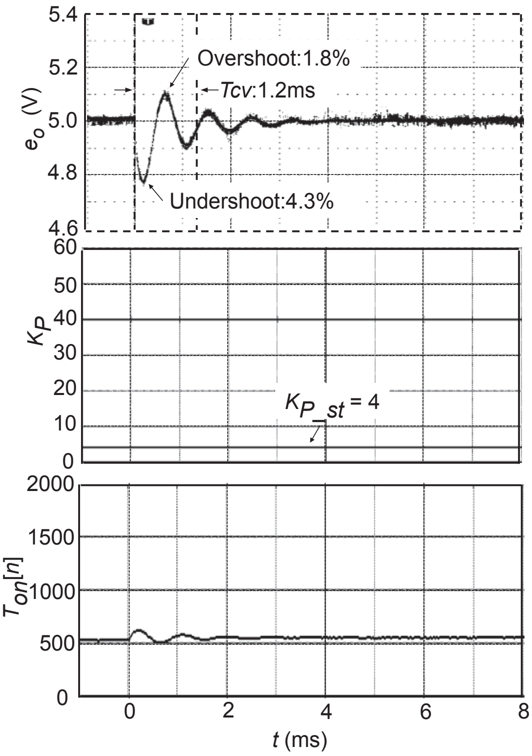

Figure 11. Waveform of e_O, K_P and T_{on}[n] of conventional PID control in transient state (E_i = 20 V).

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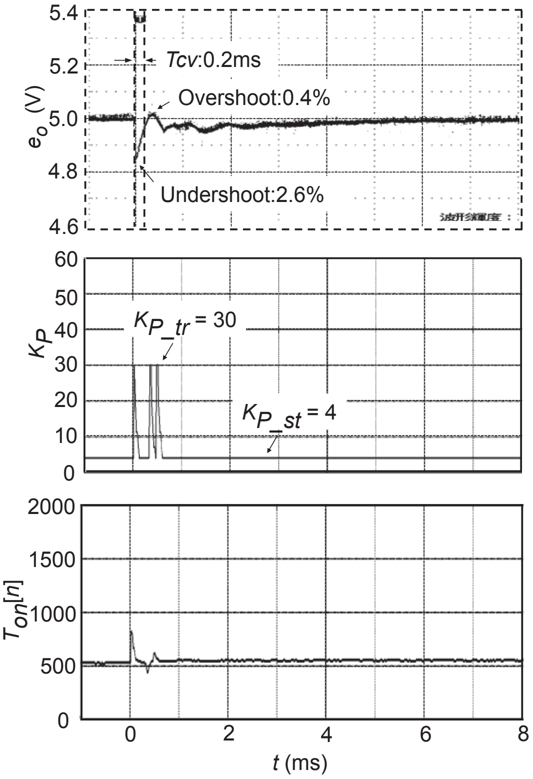

Figure 12. Waveform of e_O, K_P and T_{on}[n] of proposed method in transient state when K_{P_tr} is changed 4 to 30 (E_i = 20 V).

K_{P_st} and K_{P_tr} are equal to 4 and 30. As you can see, the transient response is similarly improved when the input voltage fluctuation occurs.

IV. EXPERIMENTAL RESULTS

Figures 11 and 12 show the transient responses in the experiment corresponding to Figs. 4 and 5. Those results match well. In Fig. 7, the undershoot, the overshoot and T_{cv} are 4.3%, 1.8% and 1.2ms, respectively. In Fig. 8, the undershoot, the overshoot and T_{cv} are 2.6%, 0.4% and 0.2ms, respectively. In concrete, the undershoot, overshoot and T_{cv} are improved by 48%, 71% and 83%, respectively. It is revealed that the proposed method is effective to improve the transient response.

V. CONCLUSION

This paper proposed a new quick response digital control dc-dc converter based on a dynamic unstable gain. 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 changing the proportional gain to the value over the stability limit temporarily in transient state. When K_P is changed from 4 to 30, the undershoot, the overshoot and T_{cv} are improved by 48%, 71% and 83%, respectively. Also, the transient response is similarly improved when the input voltage is fluctuated. The effectiveness of proposed method is corroborated in both simulation and experiment. However, K_{P_tr} should be set properly because it adversely affects the transient response when K_{P_tr} is set to extremely large value. Although the capacitance of output smoothing capacitor must be large when a large K_P is set because the system becomes unstable in the steady state, the capacitance can be reduced to 1/10 and the main circuit can be designed in small size by using the proposed method.

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