A Consideration of Loss Component in Model Control DC-DC Converter

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Abstract— **Recently, the energy saving is required. It is necessary for the energy saving to operate the electric device in the sleep mode. Therefore, the output voltage rises abnormally because the dc-dc converter is required the operation in the discontinuous current mode. Therefore, we have proposed the model control using static model and strived for improvements. In the proposed method, the output voltage is stabilized because the operating point is changed. Therefore it does not depend on the integral coefficient in principle to perform wide output voltage stabilization range. Actually, the steady state deviation remains because the model equation includes the error in the analysis. The integral control compensates it. In this paper, the static model equation and integral coefficient in the proposed method are considered based on the output voltage stabilization range.**

Keywords— dc-dc converter; digital control; model control

I. INTRODUCTION

Recently, the energy saving is required because the energy problem has become serious. The electronic device becomes sleep mode when it is not active. Thus, the power supply is operated in the light load condition. In this situation, it has the problem that the output voltage rises abnormally. The output voltage stabilization range depends on the integral gain when the dc-dc converter is controlled by the conventional digital PID control. It is necessary to increase the integral gain for wider stabilization range. On the other hand, the stability state is adversely affected by a large integral gain [1].

We have proposed the model control using static model and strived for improvements [2]-[5]. In the case of using the static model, the output voltage is stabilized because the operating point is changed by the static model. Therefore it does not depend on the integral gain in principle to perform wide output voltage stabilization range. Actually, the steady state deviation remains because the model equation includes the error in the analysis. The integral control compensates it. However, it is necessary to discuss the design of the integral gain in detail.

This paper presents the design of the integral gain in the proposed method by considering static model. The static model is compared in the cases of including loss components or not. As a result, the proper static model is derived and the integral gain which compensates the static deviation can be minimized. It is confirmed by discussing the output voltage stabilization range in the simulation. The simulation results show the calculation value of the model control in the case of considering the loss components or not. They show which one is the optimum model equation. Then the regulation characteristics using the optimization model equation are shown. The simulation and experiment characteristics are compared with each other. As a result, the necessary and minimum integral coefficient for model control is shown.

II. OPERATION PRINCIPLE

Figure 1 shows a basic configuration of the proposed method. A main circuit is a buck type dc-dc converter. e_i is the input voltage, e_o is the output voltage, R is the load resistance, R_s and e_s are the sensing resistor and voltage to detect output current i_o. e_i, e_o and e_s are detected by R_s. These are converted into the digital value. These are sent to the control circuit. Then the adequate on-time is determined in it. Figure 2 shows a configuration of the detail the control circuit. It consists of the model control and the PID control. The detected values of e_i, e_o and e_s are converted to $A_{ei}e_i$, $A_{es}e_s$ and $A_{eo}e_o$ by the pre-amplifier. The output values from the pre-amplifier are converted to digital values by the A-D converter. These are following.

$$e_i[n]= G_{AD\_ei}\, A_{ei}\, e_i \tag{1}$$

$$e_o[n]= G_{AD\_eo}\, A_{eo}\, e_o \tag{2}$$

$$e_s[n]= G_{AD\_es}\, A_{es}\, e_s \tag{3}$$

G_{AD_ei}, G_{AD_eo} and G_{AD_es} are the gain of the A-D converter gain e_i, e_o, e_s. At the control parts, e_i and e_s are used for the model control, e_o is used for the PID control. The PID control equation is given as below.

$$T_{on\_PID}[n] = K_P\left(N_R - e_o[n-1]\right) + K_I \sum N_{I,n-1} + K_D N_{D,n-1} \tag{4}$$

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The model equation $T_{on\_model}[n]$ will be described in detail at the next chapter. Each of the calculated value is subtracted. As a result the on-time $T_{on}[n]$ is obtained. The n-th on time $T_{on,n}$ of the main switch is represented by the following equation.

$$T_{on,n} = T_s \frac{T_{on}[n]}{N_{Ts}} \quad (5)$$

T_s and N_{Ts} are switching period and its digital value. The digital value on-time $T_{on}[n]$ is given as below by the model control and the PID control equation.

$$T_{on}[n] = T_{on\_model}[n] - T_{on\_PID}[n] \quad (6)$$

The static model regulates e_O because the bias is calculated for change of i_O. Therefore, it is able to obtain superior regulation characteristics without depending on the integral control.

III. CONSIDERATION OF MODEL CONTROL

In the case of the PID control, in order to expand the output voltage stabilization range, it is necessary to increase the integral coefficient because the operating point is fixed. Figure 3 shows E_O- I_O characteristics in the PID control.

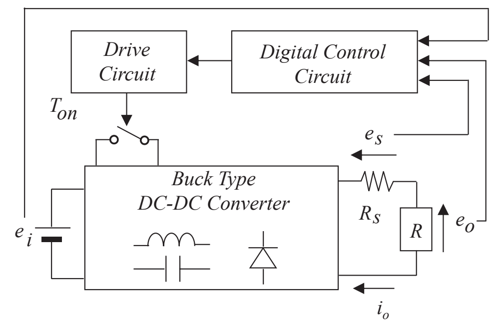


Figure 1. Basic configuration of the main circuit.

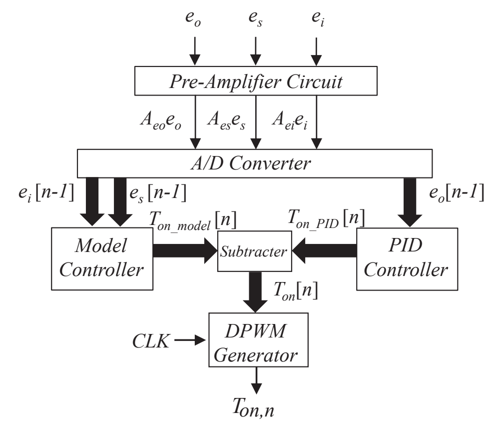


Figure 2. Configuration of the control.

It shows the output voltage stabilization range in cases of K_I = 0.000045, 0.00011 and 0.0002. According to the value of the integral coefficient is increased, the stabilization range becomes wide. In the case of the discontinuous current mode, the output voltage is increased unusually and also the on-time would be varied drastically. Therefore, a larger integral coefficient is required to expand the output voltage stabilization range covering the discontinuous current mode. In the simulation, the switching frequency f_S is 100 kHz, circuit parameters are E_i = 20 V, E_O* = 5 V, L = 196 μH, C = 891 μF and R_S = 0.05. The number of bit of A-D converter is 11 and the resolution N_{TS} of digital PWM generator is 2000. The proportional coefficient K_P is 1 and the differential coefficient K_D is 1. The upper limit value N_{I_max} of register for the integral value is set to 32000. The model equation is classified in the continuous current mode (CCM) and the discontinuous current mode (DCM). The model equation is classified into four types considering the internal loss r and diode forward voltage V_D.

A. Considering no loss components

CCM :

$$T_{on\_model\_CCM}[n] = \frac{N_{Ts}}{b} E_o^* \quad (7)$$

DCM :

$$T_{on\_model\_DCM}[n] = N_{Ts} \sqrt{\frac{2E_o^* La}{b(b - E_o^*)T_s}} \quad (8)$$

B. Considering only r

CCM :

$$T_{on\_model\_CCM}[n] = \frac{N_{Ts}}{b}\left(E_o^* + ra\right) \quad (9)$$

DCM :

$$T_{on\_model\_DCM}[n] = N_{Ts} \sqrt{\frac{2La(E_o^* + ra)}{b(b - E_o^*)T_s}} \quad (10)$$

C. Considering only V_D

CCM :

$$T_{on\_model\_CCM}[n] = \frac{N_{Ts}}{(b + V_D)}\left(E_o^* + Vd\right) \quad (11)$$

DCM :

$$T_{on\_model\_DCM}[n] = N_{Ts} \sqrt{\frac{2La(E_o^* + V_D)}{(b + V_D)(b - E_o^*)T_s}} \quad (12)$$

D. Considering r and V_D

CCM :

$$T_{on\_model\_CCM}[n] = \frac{N_{Ts}}{(b + V_D)}\left(E_o^* + ra + V_D\right) \quad (13)$$

DCM :

$$T_{on\_model\_DCM}[n] = N_{Ts}\sqrt{\frac{2La(E_o^{*} + ra + V_D)}{(b+V_D)(b-E_o^{*})T_s}} \quad (14)$$

$$a = \frac{e_s[n-1]}{A_{es}G_{AD\_es}R_s} \quad (15)$$

$$b = \frac{e_i[n-1]}{A_{ei}G_{AD\_ei}} \quad (16)$$

E_o* is the desired output voltage, and r is the total loss resistance in the dc-dc converter. CCM and DCM are switched by comparing i_o with the critical load current I_{oc}. In (15) and (16), A_{es} and G_{AD_es} are the pre-amplifier and the A-D converter gains against e_s. Similarly, A_{ei} and G_{AD_ei} are the pre-amplifier and the A-D converter gains against e_i. An advantage of the proposed method is that it does not depend on the integral coefficient to keep the output voltage stabilization range because the proposed method can optimize the operating point by varying the bias value. Figures 4 and 5 show the relationship among the on-time, the model equation and the output current in the simulation and the experiment.

In the case of (7), there is a large error against the ideal value because V_D and r in CCM are not considered. This error causes steady state deviation. Therefore, the integral coefficient should be designed to compensate it. In the case of (9), the maximum error against the ideal value is 23. Since N_{I_max} equals 32000, the necessary integral coefficient is K_I = 0.0007 (≒ 23/32000). Meanwhile, in the case of (13), the maximum error against the ideal value is 2. Thus, the necessary integral coefficient is $K_I = 0.000063$. Actually, it should be designed slightly larger than the calculated value because the error is caused by not only the model equation but also the detection. In the model control, (13) is chosen as a control equation in CCM because its error is minimum and it can minimalize the integral coefficient. When (12) and (14) are used, the maximum value of the error is 1. In the case of light load condition, (12) is valid because it has little effect on a calculation result of the model equation. Thus it is possible to design the minimum integral coefficient by using (12) and (13). Figure 6 shows the simulation results when K_I is set to 0.00011 by considering a margin. Since the output voltage is regulated at the entire range, 0.00011 is chosen as the minimum value of K_I in the model control. As Fig. 4 illustrates, the trend of the simulation and experimental results is almost similar. Thus it is possible to design the minimum integral coefficient by using (13) because (13) is near the ideal value. In Fig. 5(b), the experimental results are away from the ideal value even when any model equation is used. In the case of using the model (14) in accordance with the simulation, the error between the ideal values is at most 114. Therefore the integral coefficient is set to 0.004 by considering margin. As a result, the output voltage is able to be regulated as shown in Fig. 6 (b). When the experiment result is compared with the simulation, the model control needs a large integral coefficient because there is an error between the calculation value of the model control and the ideal value..

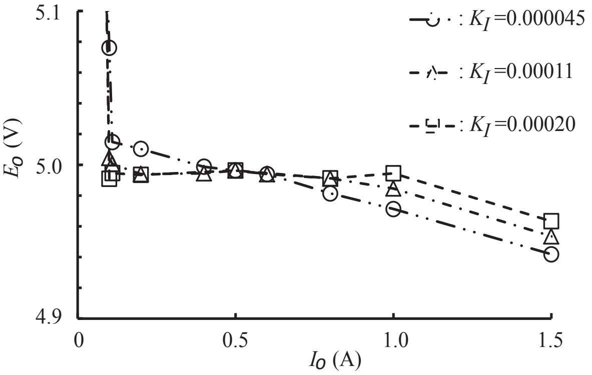
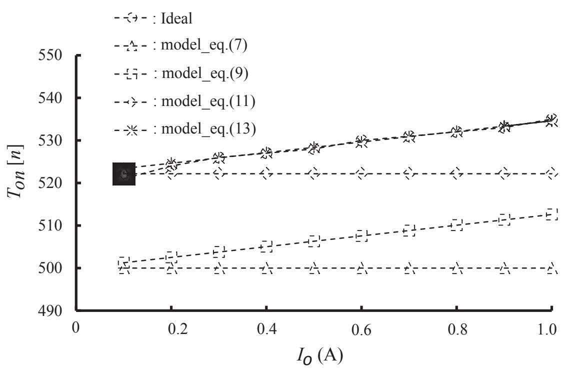
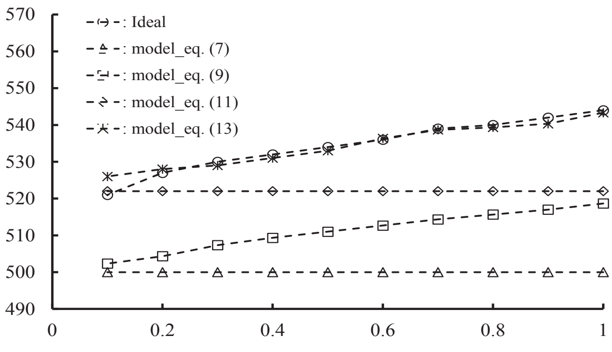


Figure 3. Steady-state characteristics (PID control).

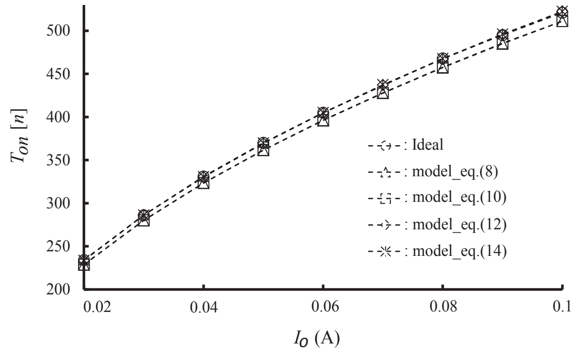


(a) Simulation

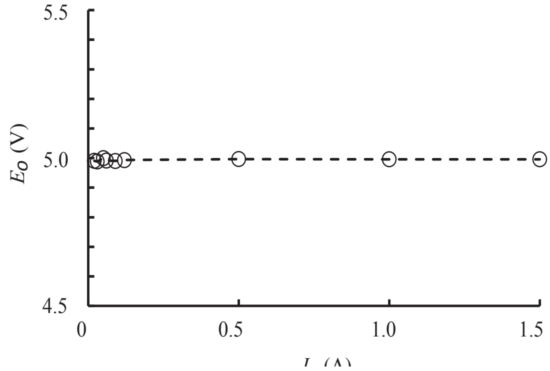


(b) Experiment

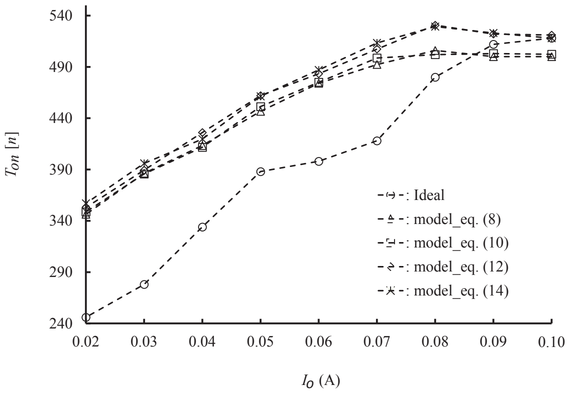
Figure 4. The on-time corresponding to the output current (CCM).



(a) Simulation

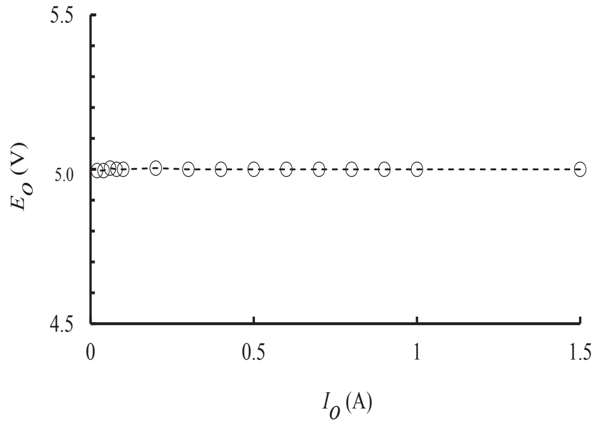


(a) Simulation



(b) Experiment

Figure 5. The on-time corresponding to the output current (DCM).



(b) Experiment

Figure 6. Steady-state characteristics (model control).

IV. CONCLUSION

In this paper, the static model equation and integral coefficient in the proposed method were considered based on the output voltage stabilization range. The static model was compared in the cases of including loss components or not. As a result, the proper static model equation was determined as (12) in DCM and (13) in CCM. Accordingly, the integral coefficient which compensates the static deviation could be minimized. The model control needs a large integral coefficient compare with the simulation. In the conventional PID control, the minimum integral gain is 0.009 in order to stabilize the output voltage in full range from 0.02A to 1.5A . On the other hand, the integral coefficient in the model control is set to 0.004. As a result, a smaller integral coefficient is able to be set for the model control compared with the conventional PID control.

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