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A New Prediction Based Digital Control for DC-DC Converter

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Abstract- As energy saving becomes important for sustainable society, one of the important social problems is to decrease the power consumption of the power converters such as those in renewable energy systems and information systems. In these application fields, the superior digital control method of power converter is needed. This paper presents a novel prediction based digitally controlled dc-dc converter. In the presented method, the prediction based control is adopted as the feedforward control added to the conventional P-I-D control as the feedback control. This prediction based control performs to control dynamical properties of the system and it is realized by a neural network approach. This neural network based control improves the transient response very effectively when the load is changed quickly. As a result, the undershoot of output voltage and the overshoot of reactor current are suppressed effectively as compared with the conventional one in the step change of load resistance. Both in simulations and experiments, it is confirmed that the presented prediction based control technique is useful to realize the superior digitally controlled method for the dc-dc converter.

Keywords- dc-dc converter; digital control; neural network; feedforward control.

1. Introduction

As energy consumption is rapidly and widely increasing, energy saving is the most important factor for the sustainable society. Since the power converter is main part in both in renewable energy systems, electronic systems and so forth, one of the important problems is to decrease the power consumption of it. To realize the low consumption of the energy in these situations, high performance power management methods for the power converter is needed. Therefore, several methods have been proposed for the power management function [1]-[3]. In the power converter system with the power management function, not only the high energy management function but also the superior dynamic characteristics are required because up and down states are changed alternately. In this case, the digital control techniques have been growing to apply to the switching power converter [4]-[8]. In the control method, the P-I-D control method, FIR (Finite Impulse Response) filter method and IIR (Infinite Impulse Response) filter method have been widely used. Since these methods are corresponding to conventional analog control methods, the intelligence and feature of digital control's own are lack in the present research. This paper presents a novel prediction based digitally controlled method of the dc-dc converter. This presented method ensures to have good static and dynamic characteristics simultaneously. In the presented method, not only the P-I-D control as the feedback control but also the new feedforward-type controllers are adopted. In the previous study [9], the model based method as the feedforward control was presented. It is realized by controlling the bias term with the model based method as the feedforward control. Addition to this previous one, the neural network predictor [10] is adopted to improve the transient response more effectively. This method is also realized by controlling the bias term with the neural network based control addition to the model based method as the feedforward control. Once the neural network is trained, the predicted data is stacked as a look-up table. This table is used as the feedforward control with the model control simultaneously. In the presented method, the P-I-D control is still remained as the feedback control. This P-I-D control works to compensate the effect of the neural network control. Therefore, the transient compensation function is added to the neural network control term against the compensation of P-I-D control. This combination of controls realizes the improvement of the dynamic and static characteristics of the circuit simultaneously. As a result, it is shown that the prediction based approach with the neural network method has a superior transient response compared with the conventional P-I-D and the model based ones. This result suggests that the neural network approach has a possibility to be used widely and easily in the control design of the dc-dc converter.

2. Operation Principle

Figure 1 shows a new multi-loop digitally controlled dc-dc converter. In this figure, E_i, R and e_o are the dc input voltage, load resistance and output voltage, respectively. L and C are the reactor and output smoothing capacitor. The controller senses the output voltage e_o, output current i_o and input voltage E_i. The output current i_o is detected as the voltage e_S by a sensing resistor R_S. Addition to above notations, E_o^* represents the desired output voltage of the presented circuit. In this case, E_o^* is equal to the reference voltage. Furthermore, N_R is the digital value of the reference voltage for digital controllers.

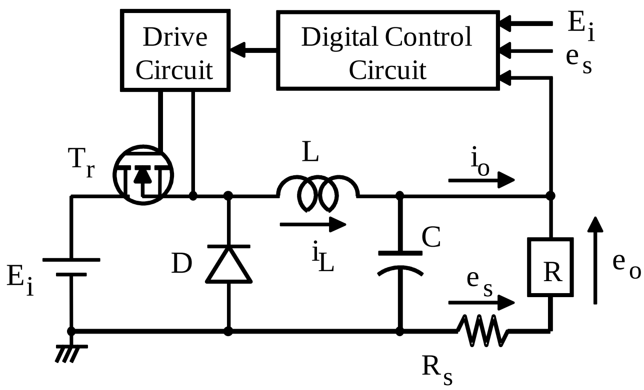

Fig. 1. Basic configuration of the presented digitally controlled dc-dc converter.

It is noticed that, in the following of this paper, the suffix *n* denotes the *n*-th period T_S of the switching period.

The on-time switching interval $T_{on,n}$ in the drive circuit is obtained from following equation.

$$T_{on,n} = \left(\frac{N_{T_{on},n}}{N_{T_S}} \right) \cdot T_S \qquad (1)$$

Here $N_{T_{on},n}$ is digitally the calculated value of the $T_{on,n}$ by the digital control circuit and N_{T_s} is the digital value of T_s. Therefore, the purpose of the controller is to obtain the optimal value of $N_{T_{on}}$.

2.1. Conventional P-I-D control

The P-I-D control is one of the widely used method for the control of dc-dc converter. The P-I-D control is a feedback control and it works to reduce the error of the output value. So it always contains the time-delay about the change of the system.

In the P, I and D controllers of the presented circuit, the output voltage $e_{o,n}$ of dc-dc converter is input to the A-D converter through a pre-amplifier circuit, and converted to the $N_{e_o,n}$. This $N_{e_o,n}$ is sent to the P-I-D controller. The controller term with the P-I-D controller is described as following;

$$N_{T_{on},n} = -N_{T_{on\_c},n} + N_B \tag{2}$$

Here N_B is the bias term which is a fixed value to drive the circuit with the feedback control and $N_{T_{on\_c},n}$ is the term of P-I-D controller. This $N_{T_{on\_c},n}$ is calculated by the following equation.

$$N_{T_{on\_c},n} = K_P(N_{e_o,n-1} - N_R) + K_I \sum N_{I,n-1} + K_D N_{D,n-1} \tag{3}$$

In Eq. (3), N_{e_o} is obtained from following equation.

$$N_{e_o,n-1} = A_{e_o} \cdot G_{e_o} \cdot e_{o,n-1} \tag{4}$$

In this conversion equation, A_{e_o} and G_{e_o} are gains of the pre-amplifier and the A-D converter which sense the output voltage. On the left side of Eq. (3), the first term is the P element of the P-I-D controller. Here K_P is the proportional coefficient. The second term is the I element where $\sum N_{I,n-1}$ is also multiplied by the integral coefficient K_I. The third term is the D element where $N_{D,n-1}$ is multiplied by the differential coefficient K_D.In this case, the integration interval is the predetermined value in the I-control and corresponds to the desired output voltage of the dc-dc converter.

2.2. P-I-D and model controls

The method presented in [9] named *model controller* was realized as the feedfoward control by controlling the bias term in Eq. (2). That is, the bias term N_B in Eq. (2) is replaced by the model controller term $N_{T_{on\_m}}$ and it is treated as a variable of the controller.

Figures 2 and 3 show the design of the model controller with the P-I-D controller. The subtractor in Fig. 2 calculates $N_{T_{on}}$ with results of P-I-D and model controllers.

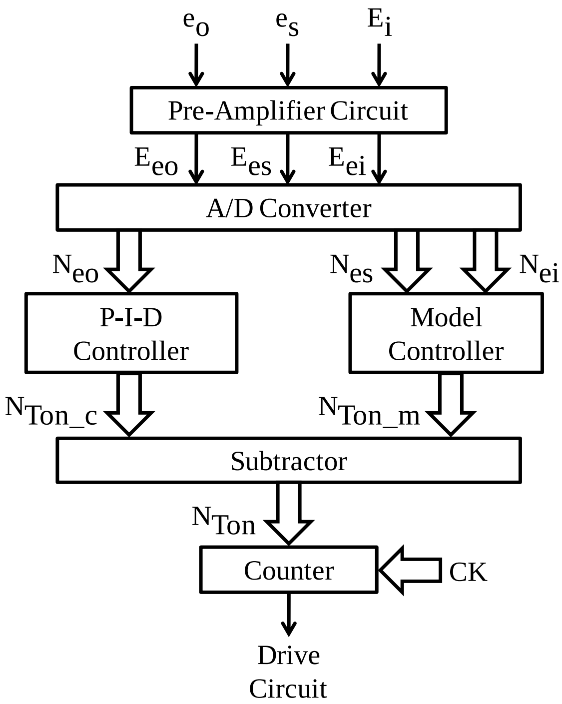

Fig. 2. Circuit configuration of model controller with P-I-D controller.

In this model controller, $N_{T_{on\_m}}$ is calculated as follows. The input voltage E_i and the output current i_o are sent to the model controller. The numerical values $N_{T_{on\_m}}$ corresponding to the on-time from the model controller are given by following Eqs. (5) and (6). In the continuous reactor current mode, $N_{T_{on\_m}}$ is given by Eq. (5) [11].

$$N_{T_{on\_m},n} = \frac{N_{T_S}}{b}\left(E_o^* + r \cdot a\right) \tag{5}$$

In the discontinuous reactor current mode $N_{T_{on\_m}}$ is given by Eq. (6) [12].

$$N_{T_{on\_m},n} = N_{T_S} \cdot \sqrt{\frac{2 \cdot E_o^* \cdot L \cdot a}{b \cdot (b - E_o^*) \cdot T_S}} \tag{6}$$

In Eqs. (5) and (6), *a*, *b*, and *r* are obtained from Eqs. (7), (8) and (9).

$$a = \frac{N_{e_S,n-1}}{A_{e_S} \cdot G_{e_S} \cdot R_S} \tag{7}$$

$$b = \frac{N_{E_i,n-1}}{A_{E_i} \cdot G_{E_i}} \tag{8}$$

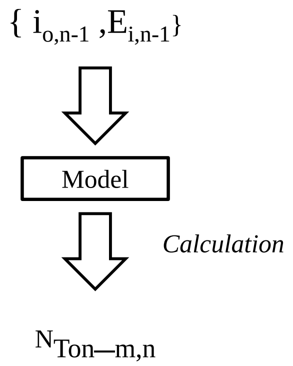

Fig. 3. Calculation process of model controller.

$$r = r_L + R_S \tag{9}$$

In Eq. (9), r_L is the internal resistance of *L*. In Eqs. (7) and (8), N_{e_S} and N_{E_i} are represented as following A-D conversion equations;

$$N_{e_S,n-1} = A_{e_S} \cdot G_{e_S} \cdot R_S \cdot i_{o,n-1} \tag{10}$$

$$N_{E_i,n-1} = A_{E_i} \cdot G_{E_i} \cdot E_{i,n-1} \tag{11}$$

In Eqs. (10) and (11), and are gains of the pre-amplifier and the A-D converter which sense the output current. Equations (7), (8) and (9) realize very simple A-D conversion, which are the results based on the analysis of analog circuit.

Using above equations, $N_{T_{on\_c}}$ and $N_{T_{on\_m}}$ are calculated and sent to the subtractor in Fig. 2. Hence the subtractor calculates the modified $N_{T_{on}}$ with P-I-D and model controllers are represented as the following equation;

$$N_{T_{on},n} = -N_{T_{on\_c},n} + N_{T_{on\_m},n} \tag{12}$$

As the model controller is described by the circuit parameters, there is no need to set other external parameters.

2.3. *Neural network based control with P-I-D and model controls*

The neural network based controller is also realized as the feedfoward control, same as the model controller, by controlling the bias term. The bias term N_B in Eq. (2) is replaced by two feedfoward control terms which are the model controller $N_{T_{on\_m},n}$ and the neural network based controller $N_{T_{on\_l},n}$.

The neural network based controller with the P-I-D and model controllers is shown in Fig. 4 and its calculation process is shown in Fig. 5, respectively. The subtractor in Fig. 4 calculates $N_{T_{on}}$ with results of P-I-D, model and neural network based controllers.

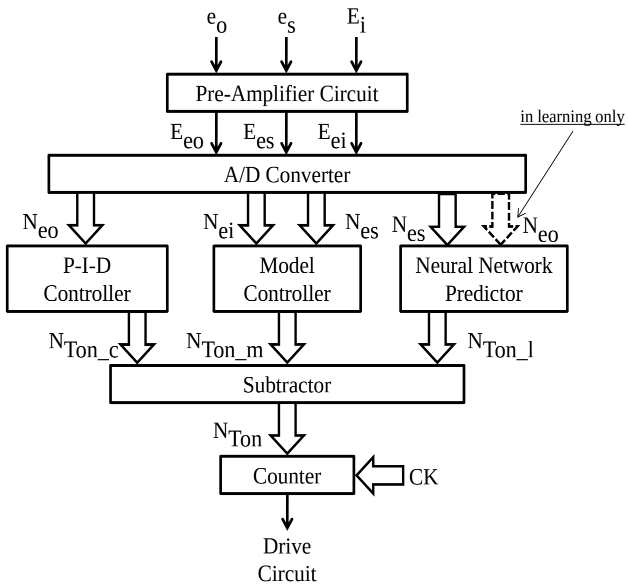

Fig. 4. Circuit configuration of neural network based controller with P-I-D and model controllers.

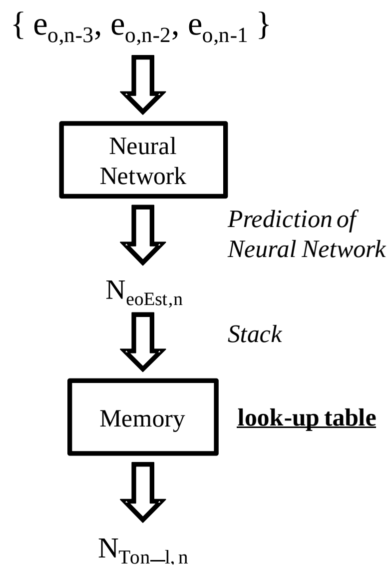

Fig. 5. Calculation process of neural network based controller for look-up table.

In the presented method, P-I-D and model controllers are still remained. The neural network based controller is considered as the predictor and mainly affects the non-linear dynamical property of the system.

The neural network predicts $e_{oEst,n}$, the *n*-th predicted value of output voltage $e_{o,n}$, using its three former data, $e_{o,n-1}$, $e_{o,n-2}$, $e_{o,n-3}$ as shown in Fig. 6. In this presented method, three-layer neural network is adopted and a sigmoid function is used as an activation function. Hence the number of the unit of input layer becomes three and the number of the hidden unit is set six, twice the number of the input layer's unit in this case. By definition, the output layer becomes one unit, which represents the predicted value $e_{oEst,n}$.

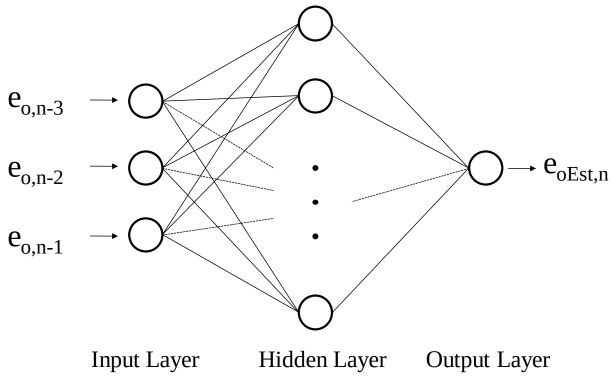

Fig. 6. Three-layer neural network for prediction.

This neural network is trained by the following process. Firstly, weight parameters of the neural network are randomly initialized. Then the neural network is trained by back propagation algorithm with the standard sum-of-squares error function. To train this neural network, one periodic data of e_o without the neural network based controller, which are obtained from the digitally controlled circuits with P-I-D and model controllers, is used as the learning data. In this case, the number of training data points is 1000 due to the switching frequency. After iterations with the back propagation algorithm using this learning data, the trained neural network is obtained. This neural network based controller is considered as the predictor of $e_{o,n}$. After $e_{oEst,n}$, which is the predicted value of $e_{o,n}$, is predicted, the feedforward controller term $N_{e_{oEst},n}$ is obtained by the substitution of the estimated $e_{o,n}$ with the neural network based controller into Eq. (4).

Therefore, the subtractor calculates the modified $N_{T_{on}}$ with the neural network based controller is represented as follows;

$$N_{T_{on},n} = -N_{T_{on\_c},n} + N_{T_{on\_m},n} + N_{T_{on\_l},n} \quad (13)$$

$$N_{T_{on\_l},n} = \alpha_n \cdot (N_R - N_{e_{oEST},n}) \quad (14)$$

$$\alpha_n = A \cdot \exp(-\lambda \cdot n) \quad (15)$$

In this method, there remains the feedback (P-I-D) control. This P-I-D control works to compensate the effect of the neural network control. Therefore, the effect of the neural network is negated when the neural network based control is used without the transient compensation function (Eq. (15)). This function is needed to obtain the effective improvement of the transient response with the neural network control. To realize it, the feedforward input of the neural network is amplified and its duration is controlled by the the multiplier α_n (Eq. (14)). This α_n , shown in Eq. (15), is an exponential-type function in which A and λ are the coefficients to compensate the input of the desired feedforward neural network based control (Fig. 7). Once {$N_{e_{oEst},n}$} are obtained, they are stacked into the memory as the look-up table, as shown in Fig. 5.

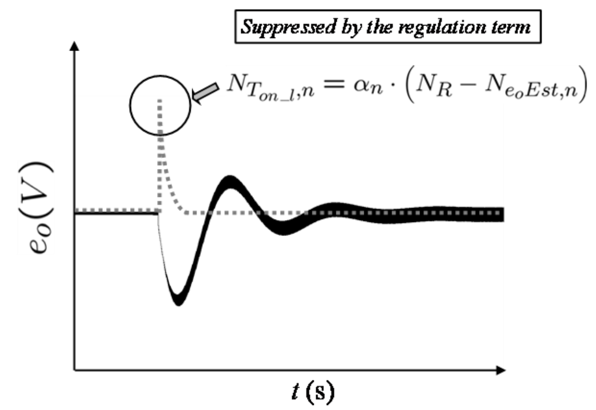

Fig. 7. Role of regulation term for suppression. Real-line represents undershoot of output voltage and dot-line represents feedforward term from neural network based control.

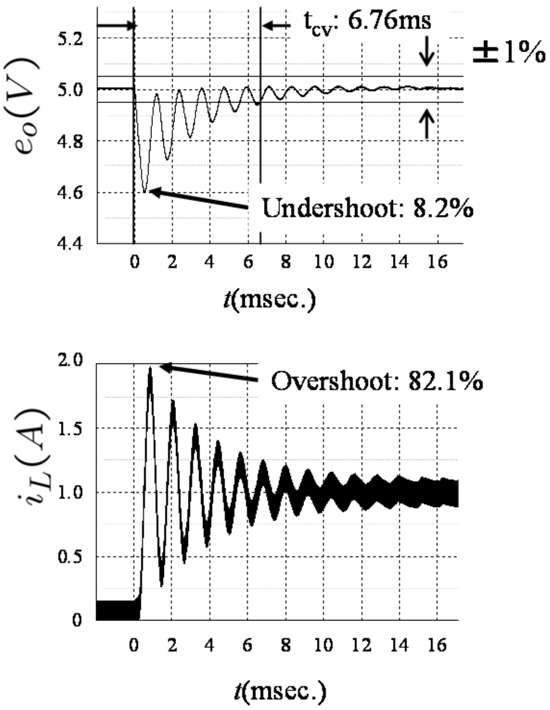

Fig. 8. Simulation result of undershoot of output voltage e_o and overshoot of reactor current i_L with P-I-D control.

As described above, the neural network based controller uses only output voltage in the learning process. However, this works to improve not only the characteristic of output voltage but also the one of reactor current shown in Sec. 3.

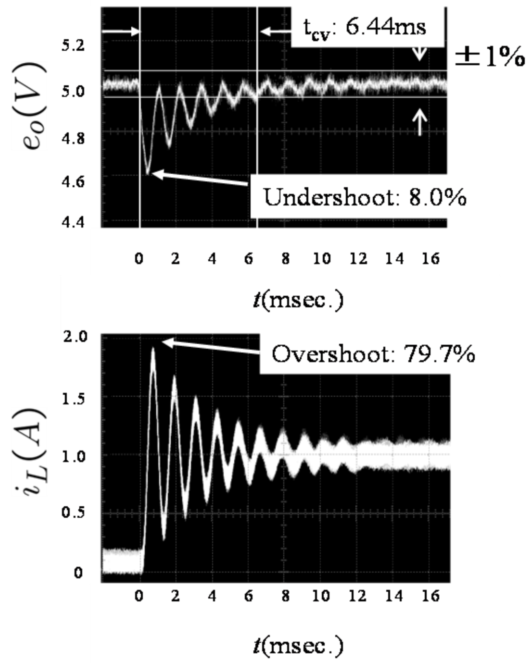

Fig. 9. Experimental result of undershoot of output voltage e_o and overshoot of reactor current i_L with P-I-D control.

This $\{N_{e_{oEst},n}\}$ is performed as the feedforward control elements with no-delay. It is sensed by the output current when the change of load is occurred. Then the predicted value $N_{e_{oEst},n}$ is obtained from the value of each load R at the previous and current time points, i.e., the value of the neural network base controller is obtained from the learned look-up table. The term of neural network based controller is calculated by Eq. (14) with this $N_{e_{oEst},n}$. Finally, the subtractor calculates $N_{T_{on},n}$ from Eq. (13).

3. Transient Responses

In this section, simulated and experimental results of transient responses are shown for the evaluation of the presented method. The simulator used here is PSIM. The switching frequency in all simulations and experiments is 100kHz. The circuit parameters are E_i=20V, E_o^*=5V, L=192μH, C=940μF, r=0.12Ω, A_{e_o}=0.25, A_{e_S} =50, A_{E_i} = 0.125, G_{e_o} = 400, G_{e_S} = 400, and G_{E_i} = 400 respectively. The bit number of A-D converter is 11 bits. These parameter settings are same among all following simulations and experiments in Sec. 3.

3.1. Comparison of P-I-D control and P-I-D and model controls

Figures 8 and 9 show the simulated and experimental transient responses of the conventional P-I-D control when the step change of the load resistor R from 100Ω (discontinuous reactor current mode) to 5Ω (continuous reactor current mode) is occurred. In these simulation and experiment, the coefficients of the P-I-D control are optimally selected to be K_P=4, K_I=0.016 and K_D=4 to achieve the best performance in the regulation characteristics and transient responses. The convergence(settling) time of the output voltage e_o, the undershoot of e_o, and the overshoot of reactor current i_L of the conventional P-I-D control are 6.44(6.76)ms, 8.0(8.2)%, and 79.7(82.1)%, respectively. Here the simulated results are shown in parentheses. From these results, it is seen that the circuit performance of the conventional type in which only P-I-D control is adopted is not so good. Especially, it is confirmed that the convergence time increases when the step change of the load resistor is occurred from the discontinuous reactor current mode to continuous reactor current mode.

Figures 10 and 11 show the simulated and experimental transient responses with P-I-D and model controls. The condition of the step change of the load resistor R is same as the case of the conventional P-I-D control. In these simulation and experiment, the circuit parameters are same as the conventional case but only K_I is different due to limit of the regulation characteristics. In this case, K_I is set to be 0.0008 optimally.

The undershoot of output voltage, overshoot of reactor current and transient time of the output voltage of model control are 3.88(3.94)ms, 3.4(3.5)%, and 75.2(75.8)%, respectively. Here the simulated results are shown in parentheses. From these results, it is seen that the addition of the model based control improves the circuit performance of the conventional P-I-D control.

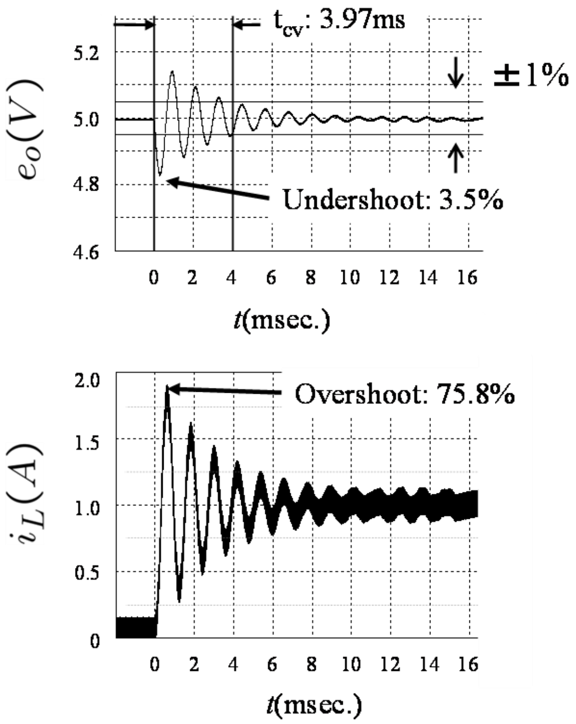

Fig. 10. Simulation result of undershoot of output voltage e_o and overshoot of reactor current i_L with P-I-D and model controls.

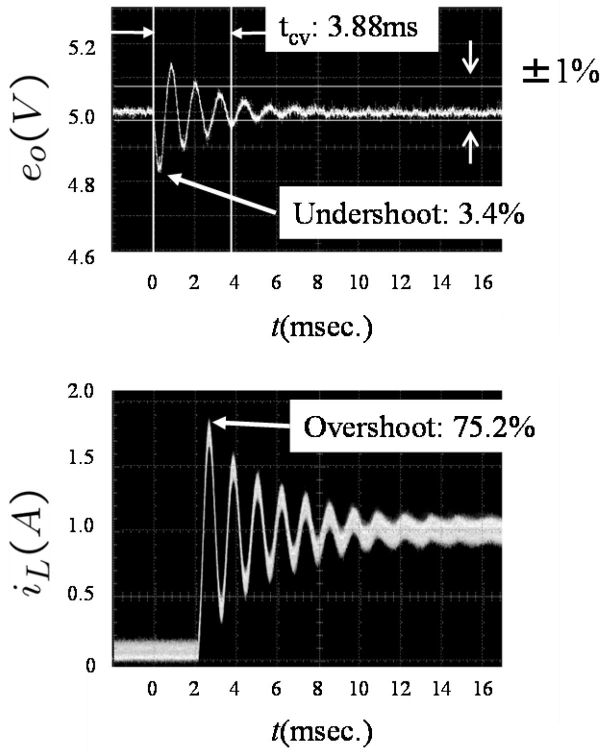

Fig. 11. Experimental result of undershoot of output voltage e_o and overshoot of reactor current i_L with P-I-D and model controls.

To improve more dramatically, the it is considered to add the neural network based control in the following.

3.2 Proposed neural network based control with P-I-D and model controls

As mentioned in Sec. 2.3, the neural network is once trained by using data of the output voltage e_o obtained from the circuit with the P-I-D and model controllers. To add the neural network based control, the regulation parameters A and λ in Eq. (15) are preliminary determined. Therefore, the optimal values of A and λ are determined by the simulation in this study.

In this simulation, the convergence time of e_o, the undershoot of e_o and the overshoot of i_L are examined when A and λ are varied. The condition of the step change of the load resistor R is same as the case in Sec. 3.1. Firstly, A is varied from 100 to 500 as the changing parameter where the step size of A is 100. Secondly, with the each value of A, λ is changed from 0.2 to 1 where the step size of λ

is 0.1. Finally, the optimal values of *A* and λ are selected so that transient responses become most suitable.

Figures 12, 13 and 14 show the results of the convergence time of e_o, the undershoot of e_o and the overshoot of i_L in this simulation, respectively.

As for the undershoot of e_o in Fig. 13, it becomes more suitable when both *A* and λ are large. Additionally, as for the overshoot of i_L in Fig. 14, it becomes suitable in same level when the λ is larger than 0.4 at any *A*. On the other hand, as for the convergence time of e_o, when the case *A* = 400 and λ = 0.4 is most suitable. From these results, the optimal values of *A* and λ are set to be 400 and 0.4 respectively. In the following simulation and experiment, these optimal values are used.

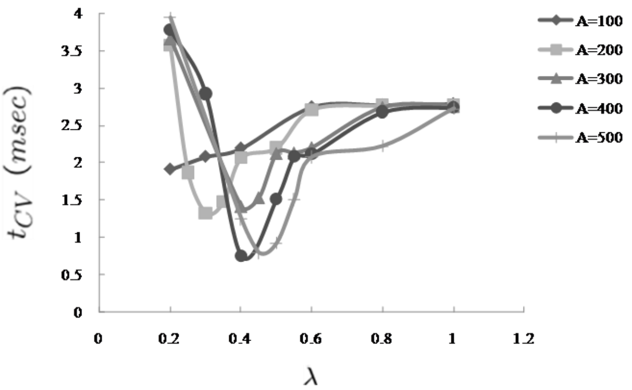

Fig. 12. Optimal value selection of *A* and λ via convergence time of e_o.

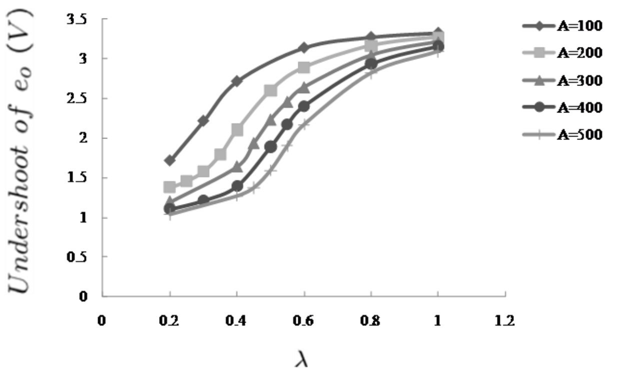

Fig. 13. Optimal value selection of A and λ via undershoot of e_o.

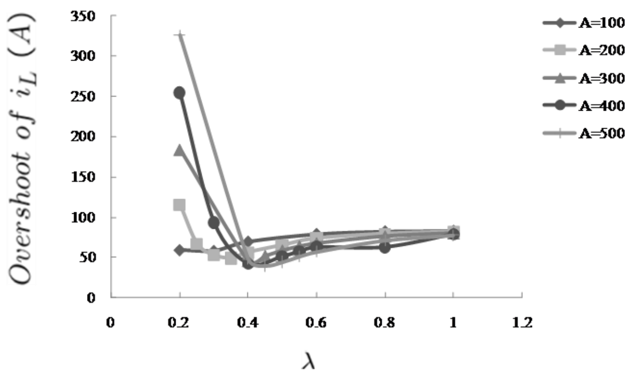

Fig. 14. Optimal value selection of *A* and λ via overshoot of i_L.

Figures 15 and 16 show the simulated and experimental results of the transient responses with the neural network based controller. The condition of the step change of the load resistor *R* is also same as the case in Sec.3.1. In these simulation and experiment, the circuit parameters are same as the P-I-D and model controllers. That is, the coefficients of the P-I-D controller are K_P = 4, K_I = 0.0008 and K_D = 4.

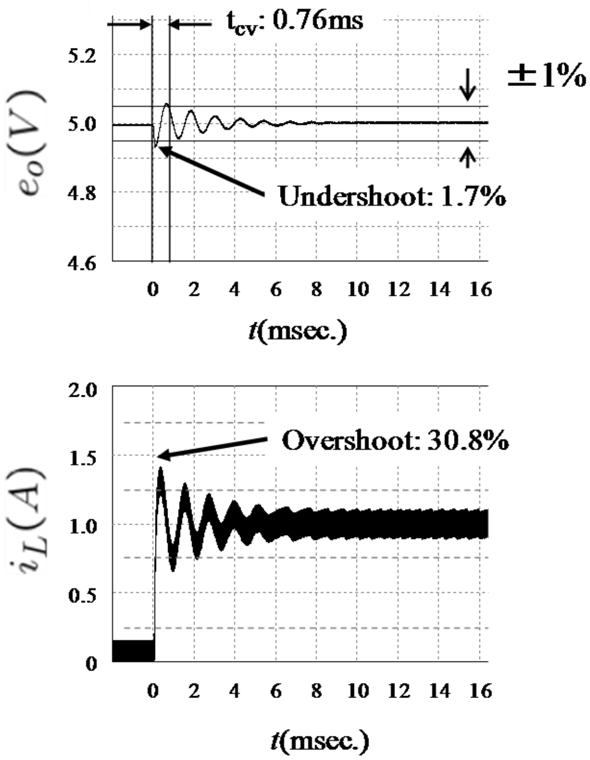

Fig. 15. Simulation result of undershoot of output voltage e_o and overshoot of reactor current i_L with P-I-D, model and neural network based controls.

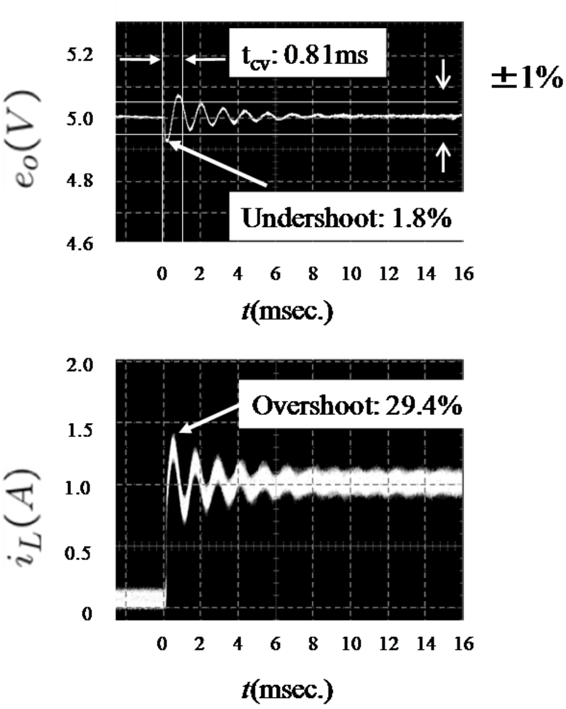

Fig. 16. Experimental result of undershoot of output voltage e_o and overshoot of reactor current i_L with P-I-D, model and neural network based controls.

The convergence time of e_o, the undershoot of e_o, the overshoot of i_L with the P-I-D, model and neural network based controls are 0.81 (0.76)ms, 1.8 (1.7) %, and 29.4 (30.8) % respectively. Here the simulated results are shown in parentheses same as above.

From these results, it is seen that the circuit with the neural network based control has the best performance among three type control methods. Hence it is also confirmed the neural network based control as the feedforward control improves the performance dramatically as for the transient responses of the circuit.

Table 1 summarizes the results of ”P-I-D control,” ”P-I-D and model controls,” and ”neural network based control with P-I-D and model controls,” respectively.

Table. 1. Summary of the results. (Simulated results are shown in parentheses.)

	P-I-D	P-I-D + model	P-I-D + model + Neural Network
Convergence time t_{CV} (ms)	6.44 (6.76)	3.88 (3.97)	**0.81 (0.76)**
Undershoot of output voltage (%)	8.0 (8.2)	3.4 (3.5)	**1.8 (1.7)**
Overshoot of reactor current (%)	79.7 (82.1)	75.2 (75.8)	**29.4 (30.8)**

4. Conclusion

This paper presents the novel prediction based digitally controlled dc-dc converter. To improve the transient response, the neural network predictor is adopted as the feedforward-type control. In both in simulations and experiments, it is clarified that the transient responses are dynamically improved with the presented method. In the neural network approach, the convergence time of output voltage and the undershoot of output voltage are improved to 12.6% and 22.5% of the conventional P-I-D control, respectively.

From the results, it is confirmed that the prediction based feedforward control improves the performance of the digitally controlled dc-dc converter effectively. It is considered that the neural network approach can be adopted to a wide range of this research area as this approach is quite simple and easy to implement. Moreover, this method supports to design the P-I-D control system to without the rigorous determination of the P-I-D coefficients. This realizes the easy design and implementation of the wide range of electronic devices.

In this study, it is not taken into account changes of circuit parameters due to aging, variation of temperatures, and other environmental conditions. In further studies, it is needed to examine the presented method about those changes and extend the method to be more robust one, for example, by adding a self-tuning system. Additionally, it is planned to apply the presented approach to other types of the circuits.

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