Digital Robust Control for DC-DC Converter with Second-Order Differential Characteristics

Kohji Higuchi¹, Eiji Takegami², Kazushi Nakano³, Tatsuyoshi Kajikawa⁴, Satoshi Tomioka⁵, Non-members, and Kosin Chamnongthai⁶, Member

ABSTRACT

Robust DC-DC converter which can covers extensive load changes and also input voltage changes with one controller is needed. The demand to suppressing output voltage changes becomes still severer. We proposed an approximate 2DOF digital controller which realizes the startup response and dynamic load response independently. The controller makes the control bandwidth wider, and at the same time makes a variation of the output voltage small at sudden changes of loads and input voltages. In this paper, a new approximate 2DOF digital control system with additional zeros is proposed. Using additional zeros second-order differential transfer characteristics between equivalent disturbances and an output voltage are realized. Therefore the new controller makes variations of the output voltage smaller at sudden changes of loads and input voltages. This controller is actually implemented on a DSP and is connected to a DC-DC converter. Experimental studies demonstrate that this type of digital controller can satisfy given severe specifications.

Keywords: DC-DC converter, Approximate 2DOF, Second-order differential, Digital robust control

1. INTRODUCTION

In many applications of DC-DC converters, loads cannot be specified in advance, i.e., their amplitudes are suddenly changed from the zero to the maximum rating. Generally, design conditions are changed for each load and then each controller is re-designed. Then, a so-called robust DC-DC converter which can cover such extensive load changes and also input voltage changes with one controller is needed. Analog control IC is used usually for control of DC-DC converter. Simple integral control etc. are performed with the analog control IC. Moreover, the application of the digital controller to DC-DC converters designed by the PID or root locus method etc. has been recently considered[1], [2]. However, it is difficult to retain sufficient robustness of DC-DC converters by these techniques. Various robust control methods for improving start-up characteristics and load sudden change characteristics of DC-DC converters are proposed[3], [4], [5], [6]. However, they take tens [ms] for the rise time of the startup responses, and hundreds [mV] output voltage regulations have arisen in the load sudden changes. The demand for suppressing output voltage change becomes still severer, and the further improvements to startup characteristics and load sudden change characteristics are required. The authors proposed the method of designing an approximate 2-degree-of-freedom (2DOF) controller of DC-DC converter[8], [9], [10], [11]. This controller realized first-order differential transfer characteristics between equivalent disturbances and an output voltage. Therefore, there is a limit in suppressing the output voltage variation, and the variation was not able to be made smaller.

In this paper, we propose a new approximate 2DOF digital controller which realizes second-order differential transfer characteristics[12], [13]. These characteristics are realized by introducing additional zeros into transfer functions between equivalent disturbances and the output. The new controller makes the variations of the output voltage smaller than the former controller[11] at sudden changes of resistive loads and input voltages. A new DC-DC converter equipped with the proposed controller in DSP is actually manufactured. Some simulations and experiments show that this new DC-DC converter can satisfy given severe specifications.

The DC-DC converter as shown in Fig.1 has been manufactured. In order to realize the approximate 2DOF digital controller which satisfies given specifications, we use the DSP(TI TMS320LF2801). This DSP has a builtin AD converter and a PWM switching signal generating part. The triangular wave carrier is adopted for the PWM switching signal. The switching frequency is set at 400[KHz] and the peak-to-peak amplitude $C_m$ is 125[V]. The LC circuit is a filter for removing carrier and switching noises. where
$C_0$ is 300[$\mu$F] and $L_0$ is 0.46[$\mu$H]. If the frequency of control signal $u$ is smaller enough than that of the carrier, the state equation of the DC-DC converter at a resistive load in Fig.1 except the controller in DSP can be expressed from the state equalizing method[14] as follows:

$$\begin{align*}
\dot{x} &= A_c x + B_c u + B_c q_u \\
y &= C x + q_y
\end{align*}$$

(1)

where

$$x = \begin{bmatrix} e_0 \\ i \end{bmatrix}, \quad A_c = \begin{bmatrix} -\frac{1}{C_0 R_L} & \frac{1}{L_0} \\ -\frac{1}{L_0} & 0 \end{bmatrix}, \quad B_c = \begin{bmatrix} 0 \\ k_p \end{bmatrix},$$

$$c = \begin{bmatrix} 1 & 0 \end{bmatrix}, \quad u = e_i, \quad y = e_o, \quad k_p = -\frac{V_i N_2}{C m N_1},$$

and $R_0$ is the total resistance of coil and ON resistance of FET, etc., whose value is 0.015[$\Omega$]. Then the discrete-time state equation of the system (1) with a zero-order hold is expressed as

$$\begin{align*}
x_d(k+1) &= A_d x_d(k) + B_d u(k) + B_d q_u(k) \\
y_k &= C x_d(k) + q_y(k)
\end{align*}$$

(2)

where

$$A_d = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = e^{A_c T}, \quad B_d = \begin{bmatrix} b_{11} \\ b_{21} \end{bmatrix} = \int_0^T e^{A_c \tau} B_c d\tau,$$

The transfer function of the system (2) is as follows:

$$G_p(z) = \frac{N_p(z)}{D_p(z)},$$

(3)

where

$$N_p(z) = b_{11} z + b_{21} a_{12} - a_{22} b_{11}.$$
and the input voltage change are considered as parameter changes in eq.(1). Such parameter changes can be transformed to equivalent disturbances \( q_u \) and \( q_y \) as shown in Fig.2 and Fig.3[15] even in discrete-time systems. Therefore, what is necessary is just to constitute the control systems whose pulse transfer functions from equivalent disturbances \( q_u \) and \( q_y \) to the output \( y \) become as small as possible in their amplitudes, in order to robustize or suppress the influence of these parameter changes and input voltage changes.

2. DESIGN METHOD FOR APPROXIMATE 2DOF DIGITAL CONTROL SYSTEM WITH ADDITIONAL ZEROS

A. Additional zeros method

The following equation is obtained by repeating the difference of the output of eq.(2):

\[
Y = O^* x_d(k) + U \bar{u}(k) + U \bar{q}_u + \bar{q}_y
\]

where

\[
Y = \begin{bmatrix} y(k) \\ y(k+1) \\ y(k+2) \end{bmatrix}, \quad O^* = \begin{bmatrix} C & CA_d \\ CA_d & CA_d^2 \end{bmatrix}, \quad U = \begin{bmatrix} 0 & 0 \\ 0 & CB_d \end{bmatrix}, \quad \bar{u}(k) = \begin{bmatrix} u(k) \\ u(k+1) \end{bmatrix}, \quad \bar{q}_u = \begin{bmatrix} q_u(k) \\ q_u(k+1) \end{bmatrix}, \quad \bar{q}_y = \begin{bmatrix} q_y(k) \\ q_y(k+1) \end{bmatrix}
\]

If both sides of eq.(4) are mutliplied by \( I_2 \) from the left, \( x_d \) is obtained by the following equation:

\[
x_d(k) = (I_2O^*)^{-1}I_2Y - (I_2O^*)^{-1}I_2U\bar{u}(k) - (I_2O^*)^{-1}I_2U\bar{q}_u - (I_2O^*)^{-1}I_2\bar{q}_y
\]

where

\[
I_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}
\]

By substituting the above equation into eq.(4), the following equation is obtained:

\[
(I_3 - O^*(I_2O^*)^{-1}I_2)U\bar{q}_u + (I_3 - O^*(I_2O^*)^{-1}I_2)\bar{q}_y = (I_3 - O^*(I_2O^*)^{-1}I_2)Y - (I_3 - O^*(I_2O^*)^{-1}I_2)U\bar{u}
\]

where \( I_3 \) is a 3 \( \times \) 3 unit matrix. That is, \( \bar{q}_u \) and \( \bar{q}_y \) can be replaced to \( Y \) and \( \bar{u}(k) \). Eq.(6) is transformed as

\[
(l_2z + l_1)q_u(k) + (z^2 + m_2z + m_1)y(k) = (l_2z + l_1)u(k) + (z^2 + m_2z + m_1)y(k)
\]

where

\[
\begin{bmatrix} l_1 & l_2 \\ m_1 & m_2 & m_3 \end{bmatrix} = (I_3 - O^*(I_2O^*)^{-1}I_2)U
\]

The system as depicted in Fig.2 is constituted in consideration of a delay time for AD conversion time etc., replacing current feedback and zeros addition. The state equation in Fig.2 can be expressed as

\[
\begin{align*}
x_{dw}(k+1) &= A_{dw}x_{dw}(k) + B_{dw}v(k) \\
y(k) &= C_{dw}x_{dw}(k)
\end{align*}
\]

where

\[
x_{dw}(k) = \begin{bmatrix} x_d(k) \\ \xi_1(k) \\ \xi_2(k) \\ \xi_3(k) \end{bmatrix}, \quad A_{dw} = \begin{bmatrix} A_d & B_d & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad B_{dw} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ C_{dw} \end{bmatrix} \quad C_{dw} = [C \ 0 \ 0 \ 0] \xi_1(k) = u(k)
\]

Applying the following feedforwards from \( q_u \), \( q_y \) and \( r \), and state feedback from \( x_{dw} \) for model matching to the system in eq.(9), the system shown in Fig.3 is obtained.
From $D(z)$, the poles of the overall system can be arranged arbitrarily by $f_1, f_2, f_3, f_4$ and $f_5$. From $N_{q_y}(z)$, two zeros of $r-y$ can be arranged arbitrarily by $g_0$ and $g_1$. Moreover, from common $N_{q_z}$ in $N_{q_z}(s)$ and $N_{q_y}(s)$, one zeros of $q_u-y$ and $q_y-y$ can be arranged arbitrarily at the same place by $k_q$. That is, one zeros can be added arbitrarily to $W_{q_y}$.

B. Design method

First, the transfer function between the reference input $r$ and the output $y$ is specified as

$$W_{r/y}(z) = \frac{N_H(z)}{D_H(z)}$$ (16)

where

$$N_H(z) = (1 + H_1)(1 + H_2)(1 + H_3)(z - n_1)(z - n_2) \times (z + H_4)(z + H_5)$$

$$D_H(z) = (1 - n_1)(1 - n_2)(z + H_1)(z + H_2)(z + H_3) \times (z + H_4)(z + H_5)$$

$n_1$ and $n_2$ are the zeros for the discrete-time controlled object (2). $[f_1 f_2 f_3 f_4 f_5, g_1 g_2]$ and $GH$ are determined so that $W_{r/y}(z)$ becomes eq.(16). And the transfer function among the disturbance inputs $q_u, q_y$ and the output $y$ is specified as

$$W_{q_u/y}(z) = (z - 1)\tilde{N}_{q_z}N_p/D_H(z)$$ (17)

$$W_{q_y/y}(z) = (z - 1)\tilde{N}_{q_z}D_p/D_H(z)$$ (18)

Here the zeros are placed at 1 by setting $k_q$ as the solution of $N_{q_z}(1) = 0$. The parameter $k_q$ becomes as follows:

$$k_q = \frac{-a_{12} + a_{12}f_5 + a_{12}f_4 + f_3a_{12} - f_2b_{11}}{a_{12}(b_{11} - a_{22}b_{11} + b_{21}a_{12})}$$ (19)

$\tilde{N}_{q_z}$ is the remaining zeros of $N_{q_z}$ which cannot be placed arbitrarily.

It shall be specified that the relation of $H_1$ and $H_2, H_3$ becomes $|H_1| \gg |Re(H_2)|, |H_1| \gg |Re(H_3)|$. Then $W_{r/y}(z)$ can be approximated to the following first-order model:

$$W_{r/y}(z) \approx W_m(z) = \frac{1 + H_1}{z + H_1}$$ (20)

This target characteristics $W_{r/y}(z) \approx W_m(z)$ is specified so as to satisfy the specs.3 and 4.

The system added the inverse system and the filter to the system in Fig.4 is constituted as shown in Fig.5. In Fig.5, the transfer function $K(z)$ becomes

$$K_z = \frac{k_z}{z - 1 + k_z}$$ (21)

The transfer functions between $r-y$, $q_u-y$, and $q_y-y$ of the system in Fig.5 are given by

$$v(k) = -k_y(l_2z + l_1)q_u(k) + k_y(z^2 + m_2z + m_1)q_y(k) + (z^2 + g_2z + g_1)r(k) + [f_1 f_2 f_3 f_4 f_5]x_{aw}(k)$$ (10)

In Fig.3, the parts surrounded by dotted lines are the feedforward coefficients from $q_u$ and $q_y$ and the part surrounded by a chain line is the estimated part of current. From eq.(7), the feedwards of eq.(10) are changed as

$$v(k) = k_y(l_2z + l_1)u(k) + k_y(z^2 + m_2Z + m_1)q_y(k) + (z^2 + g_2z + g_1)r(k) + [f_1 f_2 f_3 f_4 f_5]x_{aw}(k)$$ (11)

That is, the parts surrounded by the dotted lines are replaced by the parts surrounded by solid lines from $u$ and $y$. The system except the parts surrounded by the dotted lines in Fig.3 can be transformed equivalently as shown in Fig.4. In Fig.4,

$$ff_1 = f_1 - f_2(a_{11}/a_{12}) + k_qm_1 + f_3(k_qm_2 + f_2/a_{12}) + f_5k_qm_3 + (f_4 + f_2k_q)m_3$$

$$ff_2 = k_qm_2 + f_2/a_{12} + f_5k_qm_3$$

$$ff_3 = f_3 - f_2(b_{11}/a_{12}) + k_ql_1$$

$$ff_4 = f_4 + k_ql_2$$

$$ff_5 = f_5$$

$$ff_6 = k_qm_3$$ (12)

The transfer functions between $r$ and $y$, $q_u$ and $y$, and $q_y$ and $y$ in Fig.4 are described as

$$W_{r/y}(z) = N_{r/y}(z)/D(z)$$ (13)$$W_{q_u/y}(z) = N_{q_u/y}(z)/D(z)$$ (14)$$WW_{q_y/y}(z) = N_{q_y/y}(z)/D(z)$$ (15)

where

$$N_{r/y}(z) = GH(z^2 + g_1z + g_0)(b_{11}z + b_{21}a_{12} - a_{22}b_{11})$$

$$N_{q_u/y}(z) = N_{q_z}N_{p}$$

$$N_{q_y/y}(z) = N_{q_z}D_{p}$$

$$N_{q_z} = (a_{12}z^3 - a_{12}f_5z^2 + (a_{12}b_{11}k_q - a_{12}b_{11})z - f_3a_{12} - f_2b_{11} - a_{12}b_{22}b_{11}k_q - a_2^2f_{21}k_q)$$

$$D(z) = z^3 + (-f_5 - a_{22} - a_{11})z^4 + (a_{11}f_5 + a_{11}a_{22} - a_2a_{12} + a_{22}f_5 - f_4)z^3 + (a_{22}a_{12}f_5 - f_3 + a_4f_4 - a_{11}a_{22}f_5 + a_{22}f_5)^2 + (a_{22}f_5 + a_{22}a_{12}f_4 + a_{11}f_3 - b_{11}f_1 - f_2b_{21} - a_{12}a_{22}f_4)z + f_3a_{11}b_{21} - a_{21}f_2b_{11} + a_{21}a_{12}f_3 + f_4a_{22}b_{11} - f_1a_{12}b_{21} - a_{11}a_{22}f_5$$
Fig. 7: Simulation results of the startup responses at various loads

Fig. 8: Simulation result of the dynamic load response at resistive load

Fig. 9: Simulation result of the output response at resistive load when the input voltage changing suddenly

Fig. 10: The manufactured new quarter brick DC-DC converter

where

\[ W_s(z) = \frac{(1 + H_2)(1 + H_3)(z - n_1)(z - n_2)}{(z + H_2)(z + H_3)(1 - n_1)(1 - n_2)} \] (25)

From eqs. (26), (27) and (28), it turns out that the characteristics from \( r \) to \( y \) can be specified with \( H_1 \), and the characteristics from \( q_u \) and \( q_y \) to \( y \) can be

\[
\begin{align*}
y &\approx \frac{1 + H_1}{z + H_1} r \\
y &\approx \frac{(z - 1)^2}{z - 1 + k_z} \frac{N_q}{N_p} q_u \\
y &\approx \frac{(z - 1)^2}{z - 1 + k_z} \frac{N_q}{D_H(z)} q_y
\end{align*}
\] (26) (27) (28)
independently specified with \( k_z \). That is, the system in Fig.5 is an approximate 2DOF, and its sensitivity against disturbances becomes lower with the increase of \( k_z \).

If an equivalent conversion of the controller in Fig.5 is carried out, the approximate 2DOF digital integral-type control systems will be obtained as shown in Fig.6. In Fig.6, the parameters of the controller are as follows:

\[
\begin{align*}
k_1 &= (f_1 - f_2a_{11}/a_{12} + k_q(-a_{11}^2 - a_{21}a_{12} + a_{12}a_{11} + a_{12}a_{22})a_{11}/a_{12} + f_5(-k_q(a_{12}a_{11} + a_{12}a_{22})a_{11}/a_{12} + f_5(-k_q(a_{12}a_{11} + a_{12}a_{22})/a_{12} + f_2/a_{12}) + f_2^2k_q/(f_4 - k_qb_{11})k) - GHk_z(g_0 + (g_1 + f_5)f_5 + f_4 - k_qb_{11})/(1 + H2) \\
k_2 &= k_q - GHk_z/(1 + H2) \\
k_3 &= -k_q(a_{11}a_{12} + a_{12}a_{22})/a_{12} + f_2/a_{12} + f_5k_q - (g_1 + f_5)GHk_z/(1 + H2) \\
k_4 &= f_3 - f_2b_{11}/a_{12} + k_q((a_{12}a_{11} + a_{12}a_{22})b_{11}/a_{12} - a_{11}b_{11} - b_{21}a_{12}) \\
k_5 &= f_4 - k_qb_{11} \\
k_6 &= f_5 \\
k_7 &= (g_0 + (g_1 + f_5)f_5 + f_4 - k_qb_{11})GHk_z \\
k_8 &= (g_1 + f_5)GHk_z \\
k_9 &= GH \\
k_{10} &= (g_1 + f_5)GH \\
k_{11} &= (g_0 + (g_1 + f_5)f_5 + f_4 - k_qb_{11})GH
\end{align*}
\]

\[ (29) \]

**3. EXPERIMENTAL STUDIES**

The sampling period \( T \) are set at 2.5[\( \mu \)s]. The nominal value of \( R_L \) is 0.33[\( \Omega \)]. We design a control system so that all the specifications are satisfied. First of all, in order to satisfy the specification on the rising time of the startup transient response, \( H_1, H_2, H_3, H_4 \) and \( H_5 \) are specified as

\[
\begin{align*}
H_1 &= -0.94H_2 = -0.18 + 0.2iH_3 = -0.18 - 0.2i \\
H_4 &= -0.2 + 0.3iH_5 = -0.2 - 0.3i
\end{align*}
\]

Then from eq.(19), \( k_q = 548.31 \). After that, \( k_z \) is set up with \( k_z = 0.17 \). Then the parameters of controller become as follows:

\[
\begin{align*}
k_1 &= 861.86 \quad k_2 = 584.67 \quad k_3 = -1061.2 \\
k_4 &= 0.72688 \quad k_5 = 0.45193 \quad k_6 = -0.178811 \\
k_7 &= -1.4955 \quad k_8 = 1.2629 \quad k_9 = -2.1818(31)
\end{align*}
\]

It must be better that \( k_{11} \) and \( k_{12} \) are set to 0, since the characteristics of the control system hardly changes in this case.

The simulation results of the startup responses are shown in Fig.7. From the output voltage \( y = e_o \) in this figure, it turns out that the specifications are satisfied. It is checked that almost the same simulation results as in Fig.7 are obtained when the input voltage \( V_i \) is changed by \( \pm 20\% \). The simulation result of the dynamic load responses is shown in Fig.8. Fig.8 shows the result at resistive load whose value is changed as \( R_L = 0.33 \rightarrow 0.165[\Omega] \). It is checked that almost the same simulation result as in Fig.8 is obtained at parallel load of resistance \( R_L = 0.33 \rightarrow 0.165[\Omega] \) and capacity \( C_L = 300[\mu F] \). Fig.9 shows the output response at resistive load \( R_L = 0.33[\Omega] \) when input voltage changed suddenly as \( 48 \rightarrow 38 \rightarrow 48 \rightarrow 58 \rightarrow 48[V] \). It turns out that all the specifications are satisfied.
**Fig.14:** Experimental result of the startup response at resistive load \((R_L = 0.33[\Omega], C_L = 300[\mu F])\) when the input voltage is 58[V].

**Fig.15:** Experimental result of the dynamic load response at resistive load \((R_L = 0.33 \leftrightarrow 0.165[\Omega])\).

The manufactured, new DC-DC converter built-in DSP is shown in Fig.10. This fits in a quarter brick size (37mm \times 58mm \times 8mm) one. Experimental results when the digital controller with the parameters of eq.(31) is equipped in the DSP shown in Figs.11-18. Fig.11 shows the startup response at the resistive load \(R_L = 0.33[\Omega]\). Fig.12 shows the startup response at the resistive load \(R_L = 0.165[\Omega]\). Fig.13 shows the startup response at parallel load of resistance \(R_L = 0.33[\Omega]\) and capacity \(C_L = 300[\mu F]\). From y = eo in these figures, it turns out that almost the same experimental results as the simulation ones in Fig.7 are obtained and the specifications are satisfied. Fig.14 shows the startup response when the input voltage \(V_i\) is 58[V]. It is checked that the specifications are satisfied when the input voltage \(V_i\) is changed by 20%. Fig.15 shows the dynamic load response at resistive load \((RL = 0.33 \leftrightarrow 0.165[\Omega])\). Fig.16 shows the dynamic load response at the parallel load of resistance \((RL = 0.33 \leftrightarrow 0.165[\Omega])\) and capacity \((CL = 300[\mu F])\). It turns out that almost the same experimental results as the simulation ones in Fig.8 are obtained. Although the load current changed suddenly from 20 [A] to 10 [A], and vice versa, the output voltage change is very small and is suppressed within about 25[mV]. Fig.17 shows the output response at parallel load of resistance \((RL = 0.33[\Omega])\) and capacity \((CL = 300[\mu F])\) when input voltage changed suddenly from 38[V] to 48[V]. Fig.18 shows the output response at parallel load of resistance \((RL = 0.33[\Omega])\) and capacity \((CL = 300[\mu F])\) when the input voltage changed suddenly from 48[V] to 58[V]. It turns out that almost the same experimental results as the simulation ones in Fig.9 are obtained. It is checked that almost the same experimental results as Fig.9 are obtained when the input voltage changed suddenly from 48[V] to 58[V]. It turns out that the specifications are satisfied. We checked by experiments that all other specifications are satisfied.
4. CONCLUSIONS

In this paper, the concept of controller of DC-DC converters to attain good robustness against extensive load changes and input voltage changes was given. The proposed digital controller was implemented on the DSP (TI TMS320LF2801). The new DC-DC converter built-in this DSP was manufactured. It was shown from experiments that the sufficiently robust digital controller is realizable. The characteristics of the dynamic load responses and the output responses against sudden input voltage changes were improved by using our proposed method for approximate 2DOF digital controller with additional zeros. This fact demonstrates the usefulness and practicality of our method. The future work is to design a digital controller robust enough, when (LC+LC) circuits etc. are used as filters for removal of switching and carrier noises.

References


Kohji Higuchi received Dr. Eng. degree from Hokkaido University, Sapporo, Japan in 1981. From 1980 he was a Research Associate at the University of Electro-Communications. From 1982 he was an Assistant Professor at the University of Electro-Communications Fukuoka. He is currently an Associate Professor in the Department of Electronic Engineering, the University of Electro-Communications, Tokyo, Japan. His interests include Power Electronics and Control Engineering. He is a member of IEEE, IEICE, IEEJ and the Society of Instrument and Control Engineers (SICE).
Eiji Takegami received Dr. Eng. degree the University of Electro-Communications, Tokyo, Japan in 2008. From 1997 he was a Engineer, Development and Design of switching power supply at Nippon Electric Industry Co., Ltd. (present: TDK-LAMBDA K.K.). He is a member of IEEE, IEICE, and the Society of Instrument and Control Engineers (SICE).

Kazushi Nakano received Dr. Eng. degree from Kyushu University, Fukuoka, Japan in 1982. From 1980 he was a Research Associate at Kyushu University. From 1986 he was an Associate Professor at Fukuoka Institute of Technology. He is currently a Professor in the Department of Electronic Engineering, the University of Electro-Communications, Tokyo, Japan. His interests include system identification/control and their applications. He is a member of IEEE, IEICE, IEEJ and the Society of Instrument and Control Engineers (SICE).

Tatsuyoshi Kajikawa received B. Eng. Degree from Tokyo University of Science, Tokyo, Japan in 1990. From 1983 he was a Engineering staff in the Department of Electronic Engineering, the University of Electro-Communications, Tokyo, Japan. He is currently a Technical Official in the Department of Electronic Engineering, the University of Electro-Communications, Tokyo, Japan. His interests include Power Electronics and Control Engineering. He is a member of IEEJ.

Satoshi Tomioka received B. Eng. degree from Tokyo Denki University, Tokyo, Japan in 1984. From 1984 he is an Engineer, Development and Design of Switching Power Supply at NEMIC-LAMBDA Ltd. (present: TDK-LAMBDA K.K.).

Kosin Chamnongthai currently works as associate professor at Electronic and Telecommunication Engineering Department, Faculty of Engineering, King Mongkut’s University of Technology (KMUTT), and also serves as associate editor of ECTI-EEC Trans. He has received B.Eng. in Applied Electronic Engineering from the University of Electro-communication (UEC), Tokyo in 1985, M.Eng. in Electrical Engineering from Nippon Institute of Technology (NIT), Saitama in 1987 and D.Eng. in Electrical Engineering from Keio University, Tokyo Japan in 1991. His research interests include image processing, computer vision, robot vision, and natural language processing. He is a member of IEEE, IPS, TRS, IEICE, TESA and ECTI.