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Application of Fuzzy Integral Control for Output Regulation of Asymmetric Half-Bridge DC/DC Converter with Current Doubler Rectifier

Gyo-Bum Chung† and Sun-Geun Kwack*

†*Department of Electrical Engneering, Hongik University, Korea

ABSTRACT

This paper considers the problem of regulating the output voltage of a current doubler rectified asymmetric half-bridge (CDRAHB) DC/DC converter via fuzzy integral control. First, we model the dynamic characteristics of the CDRAHB converter with the state-space averaging method, and after introducing an additional integral state of the output regulation error, we obtain the Takagi-Sugeno (TS) fuzzy model for the augmented system. Second, the concept of parallel distributed compensation is applied to the design of the TS fuzzy integral controller, in which the state feedback gains are obtained by solving the linear matrix inequalities (LMIs). Finally, numerical simulations of the considered design method are compared to those of the conventional method, in which a compensated error amplifier is designed for the stability of the feedback control loop.

Keywords: Asymmetric Half Bridge DC/DC converter, Current Doubler Rectification, Takagi-Sugeno Fuzzy Model, Integral Control, Regulation, Linear Matrix Inequality, Compensated Error-Amplifier

1. Introduction

Recently, with rapid progress made in power semi-conductor applications, the needs for high-performance control have dramatically increased in many areas. In particular, the methods of LQG control, H^{∞} control and fuzzy control have been successfully applied to achieve the stability, robustness, and the output-regulation for switching power converters such as current doubler rectified asymmetric half-bridge (CDRAHB) DC/DC converter[1,2], boost converter[3,4], and buck converter[5,6]. Among the results, the Takagi-Sugeno (TS) fuzzy integral control approach which was recently proposed by Lian .et al.[5] turns out to be very promising, since it guarantees the stable output-regulation as well as the robustness and disturbance rejection capability. Motivated by the recent successful applications of the TS fuzzy integral control method to various type of converters[5,6], this paper considers the problem of applying the method to the output-regulation of the CDRAHB DC/DC converter. The CDRAHB DC/DC converter has been known to have many advantages in the area of the power conversion[1,2], and due to the nonlinear characteristics of the converter system, maintaining its output voltage constant regardless of the output load changes has been known to be a difficult task. The

Manuscript received Feb. 21,2007; revised May 31,2007
†Corresponding Author:gbchung@wow.hongik.ac.kr
Tel: +82-41-860-2595, Fax: +82-41-863-7605, Hongik Univ.
* Dept. of Electrical Eng., Hongik University

remaining parts of this paper are organized as follows: Section 2 presents the modeling process for the CDRAHB DC/DC converter. Section 3 describes how to apply the integral TS fuzzy control to the output regulation of the converter. Finally, in Sections 4 and 5, simulation results and concluding remarks are given, respectively.

2. Current Doubler Rectified Asymmetric Half-Bridge Converter

Fig. 1 shows a CDRAHB DC/DC converter with a fuzzy integral controller to regulate the output voltage V_O for a resistive load R. Switch S_1 with duty ratio d and switch S_2 with duty ratio (1-d) operate complementarily in a constant switching period T[1,2,7]. N_P is the number of turns on the primary winding of transformer T_x. N_s is the number of turns on the secondary winding.

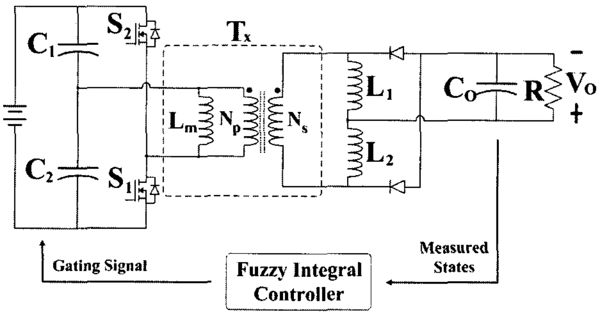

Fig. 1 Power circuit of the asymmetric half-bridge DC/DC converter

For the analysis of the converter operation, the parasitic resistances of the inductor and capacitors are considered. It is assumed that $n = N_s / N_p$. However, the dead time between S_1 and S_2, the leakage inductance of transformer T_X, and diode voltage drop are neglected.

When switch S_1 is on and switch S_2 is off for $0 \le t \le dT$, the CDRAHB DC/DC converter in Fig.1 can be described by

$$\dot{x} = A_1 \cdot x + B_1 \cdot V_i \qquad y = C_1 \cdot x \tag{1}$$

where

$$x^T = \begin{bmatrix} v_{ci} & i_{L1} & i_{L2} & v_{co} \end{bmatrix}, \tag{2}$$

$$A_1 = \begin{bmatrix} 0 & n/C_i & 0 & 0 \\ -n/L_1 & a_{22,1}/L_1 & R_{p1}/L_1 & -R_{p2}/L_1 \\ 0 & R_{p1}/L_2 & -(R_{L2}+R_{p1})/L_2 & R_{p2}/L_2 \\ 0 & R_{p2}/C_o & -R_{p2}/C_o & -1/(R_{Co}+R)/C_o \end{bmatrix}$$

$$a_{22,1} = -\left[R_{L1} + R_{Co} \cdot R/(R_{Co}+R) + n^2 \cdot R_{Ci}\right]$$

$$R_{p1} = R_{Co} R/(R_{Co}+R)$$

$$R_{p2} = R/(R_{Co}+R)$$

$$B_1^T = \begin{bmatrix} 0 & n/L_1 & 0 & 0 \end{bmatrix}$$

$$C_1 = \begin{bmatrix} 0 & R_{p1} & -R_{p1} & R_{p2} \end{bmatrix}$$

When switch S_1 is off and switch S_2 is on for $(1-D)T \le t \le T$, the CDRAHB DC/DC converter in Fig. 1 can be described by

$$\dot{x} = A_2 \cdot x + B_2 \cdot V_i \qquad y = C_2 \cdot x \tag{3}$$

where

$$A_2 = \begin{bmatrix} 0 & 0 & n/C_i & 0 \\ 0 & -(R_{L1}+R_{p1})/L_1 & R_{pp}/L_1 & -R_{p2}/L_1 \\ -n/L_2 & R_{pp}/L_2 & a_{33,2}/L_2 & R_{p2}/L_2 \\ 0 & R_{p2}/C_o & -R_{p2}/C_o & -1/(R_{Co}+R)/C_o \end{bmatrix} \tag{4}$$

$$a_{33,2} = -\left[R_{L2} + R_{Co} \cdot R/(R_{Co}+R) + n^2 \cdot R_{Ci}\right]$$

$$B_2^T = \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C_2 = \begin{bmatrix} 0 & R_{p1} & -R_{p1} & R_{p2} \end{bmatrix}$$

State-space-averaged representation of the CDRAHB DC/DC converter is written as follows

$$\begin{aligned} \dot{x} &= A_a \cdot x + B_a \cdot V_i \\ &= \left[d \cdot A_1 + (1-d) \cdot A_2\right] \cdot x + \left[d \cdot B_1 + (1-d) \cdot B_2\right] \cdot V_i \\ y &= C_a \cdot x \\ &= \left[d \cdot C_1 + (1-d) \cdot C_2\right] \cdot x \end{aligned} \tag{5}$$

where

$$A_a = \begin{bmatrix} 0 & d \cdot n/C_i & (1-d) \cdot n/C_i & 0 \\ -d \cdot n/L_1 & -(R_{L1}+R_{p1}+d \cdot n \cdot n \cdot R_{Ci})/L_1 & R_{p1}/L_1 & -R_{p2}/L_1 \\ -(1-d) \cdot n/L_2 & R_{p1}/L_2 & -(R_{L2}+R_{p1}+(1-d) \cdot n \cdot n \cdot R_{Ci})/L_2 & -R_{p2}/L_2 \\ 0 & R_{p2}/C_o & -R_{p2}/C_o & -1/(R_{Co}+R)/C_o \end{bmatrix} \tag{6}$$

$$B_a^T = \begin{bmatrix} 0 & d \cdot n/L_1 & 0 & 0 \end{bmatrix}$$

$$C_a = \begin{bmatrix} 0 & R_{p1} & -R_{p1} & R_{p2} \end{bmatrix}$$

Dynamic behavior of the converter can be described in terms of small signal variations around a steady-state operation point[1,2,7]. The perturbed duty ratio, input voltage and states are represented as

$$x = X + \tilde{x}$$
$$v_I = V_I + \tilde{v}_i \tag{7}$$
$$d = D + \tilde{d}$$

Substituting the perturbed variables of (7) to (5), the small-signal ac dynamic model of the converter in Fig. 1 can be obtained as

$$\begin{aligned} \dot{\tilde{x}} &= A_s \cdot \tilde{x} + B_s \cdot \tilde{d} + E_s \cdot \tilde{v}_i \\ \tilde{y} &= C_s \cdot \tilde{x} \end{aligned} \tag{8}$$

where

$$A_s = \begin{bmatrix} 0 & D \cdot n/C_i & (1-D) \cdot n/C_i & 0 \\ -D \cdot n/L_1 & a_{22s} & R_{p1}/L_1 & -R_{p2}/L_1 \\ -(1-D) \cdot n/L_2 & R_{p1}/L_2 & a_{33s} & R_{p2}/L_2 \\ 0 & R_{p2}/C_o & -R_{p2}/C_o & -1/(R_{Co}+R)/C_o \end{bmatrix}$$

$$a_{22,s} = -(R_{L2} + R_{p1} + (1-D) \cdot n \cdot n \cdot R_{Ci}) / L_2$$

$$a_{33,s} = -(R_{L1} + R_{p1} + D \cdot n \cdot n \cdot R_{Ci}) / L_1 \tag{9}$$

$$B_s = \begin{bmatrix} n\left(I_{L1} + \tilde{i}_{L1} - I_{L2} + \tilde{i}_{L2}\right)/C_i \\ -n\left[\left(V_{Ci} + \tilde{v}_{Ci}\right) - n \cdot R_{Ci}\left(I_{L1} + \tilde{i}_{L1}\right) - V_i\right]/L_1 \\ n\left[\left(V_{Ci} + \tilde{v}_{Ci}\right) + n \cdot R_{Ci}\left(I_{L2} + \tilde{i}_{L2}\right)\right]/L_1 \\ 0 \end{bmatrix}$$

$$E_s^T = \begin{bmatrix} 0 & nD & 0 & 0 \end{bmatrix}$$

$$C_s = \begin{bmatrix} 0 & R_{p1} & -R_{p1} & R_{p2} \end{bmatrix}$$

The output regulation can be achieved with adding an extra error state, $x_e = \int (V_r - y) \cdot dt$, where V_r is the reference signal for the output voltage V_o and the small-signal ac dynamic model of the converter added with the error state is rewritten as follows:

$$\dot{\tilde{x}} = A_x \cdot \tilde{x} + B_x \cdot \tilde{d} + E_x \cdot \tilde{v}_i \tag{10}$$

$$\tilde{y} = C_x \cdot \tilde{x}$$

where

$$x^T = \begin{bmatrix} \tilde{v}_{ci} & \tilde{i}_{L1} & \tilde{i}_{L2} & \tilde{v}_{co} & \tilde{x}_e \end{bmatrix}$$

$$A_x = \begin{bmatrix} 0 & D n/C_i & (1-D) \cdot n/C_i & 0 & 0 \\ -D n/L_1 & a_{22s} & R_{p1}/L_1 & -R_{p2}/L_1 & 0 \\ -(1-D) \cdot n/L_2 & R_{p1}/L_2 & a_{33s} & R_{p2}/L_2 & 0 \\ 0 & R_{p2}/C_o & -R_{p2}/C_o & -1/(R_{Co}+R)/C_o & 0 \\ 0 & -R_{p1} & R_{p1} & -R_{p2} & 0 \end{bmatrix}$$

$$B_x = \begin{bmatrix} n\left(I_{L1} + \tilde{i}_{L1} - I_{L2} + \tilde{i}_{L2}\right)/C_i \\ -n\left[\left(V_{Ci} + \tilde{v}_{Ci}\right) - n \cdot R_{Ci}\left(I_{L1} + \tilde{i}_{L1}\right) - V_i\right]/L_1 \\ n\left[\left(V_{Ci} + \tilde{v}_{Ci}\right) + n \cdot R_{Ci}\left(I_{L2} + \tilde{i}_{L2}\right)\right]/L_1 \\ 0 \\ 0 \end{bmatrix} \tag{11}$$

$$E_x^T = \begin{bmatrix} 0 & nD & 0 & 0 & 0 \end{bmatrix}$$

$$C_x = \begin{bmatrix} 0 & R_{p1} & -R_{p1} & R_{p2} & 0 \end{bmatrix}$$

3. Design of Integral TS Fuzzy Control via LMIs

In this section, we apply an integral TS fuzzy control approach to regulating the output of the CRDAHB DC/DC converter. Here, we follow the strategy of Lian et al.[5] with a slight modification to design the fuzzy controller, and the design strategy is composed of the following steps: First, the additional integral error signal is introduced to form the augmented system consisting of the converter dynamics and error dynamics. Second, the standard TS fuzzy model is established with the new coordinates centered at the regulated points. Finally, the concept of parallel distributed compensation[8] is applied to design the TS fuzzy controller, in which the state feedback gains are obtained by solving LMIs[9] via MATLAB. In the following, we will explain the design procedure in a step-by-step manner:

According to the modeling of Section 2, the considered converter system belongs to the following general class of nonlinear systems:

$$\begin{aligned} \dot{x}_p(t) &= f\left(x_p(t), d(t)\right) \\ y(t) &= h\left(x_p(t)\right) \end{aligned} \tag{12}$$

where $x_p(t) \in R^n$, $d(t) \in R$, $y(t) \in R$ are the state, the control input, and the output, respectively. For this system, let $r \in R$ be a constant desirable reference, and we want to design a controller achieving the goal $y(t) \to r$ as $t \to \infty$. For this goal, we will use the integral TS fuzzy control[5], which belongs to the integral-type controllers and thus can not only achieve zero steady-state regulation error but also be robust against uncertainty and disturbance. In the integral control, a state variable $x_e(t)$ is additionally introduced to account for the integral of the output regulation error, and thus it satisfies

$$\dot{x}_e(t) = r - y(t) \tag{13}$$

Incorporating the error dynamics for the output signal to the original nonlinear system (12), one can obtain the following augmented state equation:

$$\begin{aligned} \dot{x}_p(t) &= f(x_p(t), d(t)) \\ \dot{x}_e(t) &= r - h(x_p(t)) \end{aligned} \tag{14}$$

Here, the output regulation can be achieved by stabilizing the whole system around an equilibrium state which can yield $y = h(x_p)$ being equal to r. For this, let $\bar{x}_p \in R^n$ and $\bar{d} \in R$ be such that

$$\begin{aligned} f(\bar{x}_p, \bar{d}) &= 0 \\ r - h(\bar{x}_p) &= 0 \end{aligned} \tag{15}$$

and let $\tilde{x}_p$, $\tilde{x}_e$ and $\tilde{d}$ be the new coordinates centered at the regulated points, i.e., $\tilde{x}_p = x_p - \bar{x}_p$, $\tilde{x}_e = x_e - \bar{x}_e$ and $\tilde{d} = d - \bar{d}$. Here, the control input $d(t)$ is a function of the state variables $x_p(t)$ and $x_e(t)$, i.e., $d(t) = k(x_p(t), x_e(t))$, where $k(\cdot,\cdot)$ represents the control law, thus the equilibrium points $\bar{x}_p$, $\bar{d}$ and $\bar{x}_e$ should satisfy $\bar{d} = k(\bar{x}_p, \bar{x}_e)$, and from this equality, $\bar{x}_e$ can be determined. Note that (14) can now be expressed using the new coordinates as follows:

$$\begin{aligned} \dot{\tilde{x}}_p(t) &= f(\bar{x}_p + \tilde{x}_p(t), \bar{d} + \tilde{d}(t)) = f_0(\tilde{x}_p(t), \tilde{d}(t)) \\ \dot{\tilde{x}}_e(t) &= r - h(\bar{x}_p + \tilde{x}_p(t)) = h_0(\tilde{x}_p(t)) \end{aligned} \tag{16}$$

Also note that in (16), the newly defined functions, f_o and h_o, satisfy $f_o(0,0)=0$ and $h_o(0)=0$, respectively. From the modeling of the previous section, it is observed that the augmented system (16) for the CRDAHB DC/DC converter can be represented by the TS fuzzy model, in which the i-th rule has the rule, has the following form:

Plant Rule i:

$$\begin{aligned} &\text{IF } z_1(t) \text{ is } F_1^i \text{ and } \cdots z_g(t) \text{ is } F_g^i, \\ &\text{THEN } \dot{\tilde{x}}(t) = A_i \cdot \tilde{x}(t) + B_i \cdot \tilde{d}(t), \end{aligned} \tag{17}$$

where $i=1,\cdots, m$. Here, $\tilde{x}(t) = [\tilde{x}_p^T(t) \quad \tilde{x}_e(t)]^T$ is the state vector; $z_j(t)$, $j=1,\cdots, g$ are premise variables each of which is selected from the entries of $x_p(t)$; F_j^i, $j=1,\cdots, g$, $i=1,\cdots, m$ are fuzzy sets; m is the number of IF-THEN rules, and (A_i, B_i) is the i-th local model of the fuzzy system. Utilizing the usual inference method, one can obtain the following state equation for the TS fuzzy system[8]:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{m} \mu_i(x_p(t))\{A_i \cdot \tilde{x}(t) + B_i \cdot \tilde{d}(t)\} \tag{18}$$

where the normalized weight functions $\mu_l(x_p(t)) = w_l(x_p(t)) / \sum_i w_i(x_p(t))$ with $w_l(x_p(t)) = \prod_{j=1}^{g} F_j^l(x_p(t))$ satisfy

$$\mu_l(x_p) \geq 0, \quad l=1,\cdots, m, \tag{19}$$

and

$$\sum_{l=1}^{m} \mu_l(x_p) = 1 \quad \text{for any} \quad t \geq 0. \tag{20}$$

For simplicity, the normalized weight function $\mu_i(x_p(t))$ will be denoted by μ_i from now on. According to the concept of the parallel distributed compensation[8], the TS fuzzy system (18) can be effectively controlled by the TS fuzzy controller, which is described by the following IF-THEN rules :

Controller Rule i:

$$\text{IF } z_1(t) \text{ is } F_1^i \text{ and } \cdots z_g(t) \text{ is } F_g^i, \qquad (21)$$
$$\text{THEN } \tilde{d}(t) = -K_i\tilde{x}(t)$$

where l=1,⋯, m. Note that the IF part of the above controller rule shares the same fuzzy sets with that of (17). The usual inference method for the TS fuzzy model yields the following representation for the TS fuzzy controller[8]

$$\tilde{d}(t) = -\sum_{i=1}^{m}\mu_i \cdot K_i \cdot \tilde{x}(t) \qquad (22)$$

and plugging (22) into (18) yields the closed-loop system represented as

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{m}\sum_{j=1}^{m}\{\mu_i\mu_j \cdot (A_i - B_i \cdot K_j)\cdot \tilde{x}(t)\} \qquad (23)$$

Here, the state feedback gains K_i can be found by solving the LMIs of the following theorem, which is obtained combining Theorem 1 of [5] together with Theorem 2.2 of [10].

Theorem: Let D be a diagonal positive-definite matrix. The closed-loop (23) can be exponentially stabilized via the controller (22) with $K_j = M_jX^{1}$ if there exists $X = X^T > 0$ and $M_1, \cdots, M_m$ satisfying the following LMIs:

$$N_{ii}(Y) < 0, i = 1,\cdots,m$$
$$\frac{1}{m-1}N_{ii}(Y) + \frac{1}{2}\left(N_{ij}(Y) + N_{ji}(Y)\right) < 0, \qquad 1 \le i \ne j \le m, \qquad (24)$$

where

$$Y = (X, \ M_1, \ \cdots, \ M_m)$$
$$N_{ij}(Y) = \begin{bmatrix} A_i^T X + XA_i - B_iM_i - M_j^T B_i^T & XD^T \\ DX & -X \end{bmatrix} \qquad (25)$$

4. Design Example and Simulation

In this section, we present an example of the TS fuzzy control approach described above applied to the problem of regulating the output voltage of the CRDAHB DC/DC converter. Numerical simulations with PSIM[11] are carried out to show the performance of the integral TS fuzzy controller and to compare with the conventional loop-gain design method[12]. We consider the converter with the system parameters of Table 1[1], and its equilibrium points satisfying (15) are as follows:

$$\bar{x}_p = \begin{bmatrix}\bar{v}_{ci} & \bar{i}_{L1} & \bar{i}_{L2} & \bar{v}_{co}\end{bmatrix}^T = \begin{bmatrix}117.97, & 14.14, & -6.06, & 48.49\end{bmatrix}^T$$

and $\bar{d} = 0.3$.

Table 1 Parameters of the the asymmetric half-bridge DC/DC converter[1]

Parameters	Value	Unit
Input Voltage, V_i	400	V
Input Capacitor, C_i	10	μF
Parasitic Resistance for C_i, R_i	0.1	Ω
Magnetizing Inductance, L_m	∞	μH
Output Inductance, L_1	40	μH
Parasitic Resistance for L_1, R_{L1}	0.15	Ω
Output Capacitance, C_O	1000	μF
Parasitic Resistance for C_O, R_o	0.01	Ω
Output Resistance, R	2.4	Ω
Transformer Turn Ratio (N_s/N_p), n	0.6	
Switching Frequency, f_s	100	kHz
Nominal output voltage, V_o	48	V

As mentioned before, substituting $x_p(t) = \bar{x}_p + \tilde{x}(t)$, $x_e(t) = \bar{x}_e + \tilde{x}_e(t)$, and $d(t) = \bar{d} + \tilde{d}(t)$ into (5) and (13) yields the augmented system (10), which can be represented as the TS fuzzy IF-THEN rules (17). Here, with h_{ci}=20, h_{L1}=50 and h_{L2}=50, the membership functions of (17) are defined as follows:

$$F_1^1(\tilde{v}_{ci}) = F_1^2(\tilde{v}_{ci}) = F_1^3(\tilde{v}_{ci}) = F_1^4(\tilde{v}_{ci}) = \frac{1}{2}\left[1 + \frac{\tilde{v}_{ci}(t)}{h_{ci}}\right]$$
$$F_1^5(\tilde{v}_{ci}) = F_1^6(\tilde{v}_{ci}) = F_1^7(\tilde{v}_{ci}) = F_1^8(\tilde{v}_{ci}) = \frac{1}{2}\left[1 - \frac{\tilde{v}_{ci}(t)}{h_{ci}}\right] \qquad (26)$$

$$F_2^1(\tilde{i}_{L1})=F_2^2(\tilde{i}_{L1})=F_2^5(\tilde{i}_{L1})=F_2^6(\tilde{i}_{L1})=\frac{1}{2}\left[1+\frac{\tilde{i}_{L1}(t)}{h_{L1}}\right]$$

$$F_2^3(\tilde{i}_{L1})=F_2^4(\tilde{i}_{L1})=F_2^7(\tilde{i}_{L1})=F_2^8(\tilde{i}_{L1})=\frac{1}{2}\left[1-\frac{\tilde{i}_{L1}(t)}{h_{L1}}\right]$$

$$F_2^2(\tilde{i}_{L2})=F_2^4(\tilde{i}_{L2})=F_2^6(\tilde{i}_{L2})=F_2^8(\tilde{i}_{L2})=\frac{1}{2}\left[1-\frac{\tilde{i}_{L2}(t)}{h_{L2}}\right]$$

$$F_3^1(\tilde{i}_{L2})=F_3^3(\tilde{i}_{L2})=F_3^5(\tilde{i}_{L2})=F_3^7(\tilde{i}_{L2})=\frac{1}{2}\left[1+\frac{\tilde{i}_{L2}(t)}{h_{L2}}\right]$$

Also, the resultant local models $(A_i,\ B_i)$, i=1,...,8 obtained by plugging the parameter values of Table 1 are as follows

$$A_1=\cdots=A_8=10^4\times\begin{bmatrix}0 & 1.8000 & 4.2000 & 0 & 0\\ -0.45 & -0.4269 & 0.0249 & -2.4849 & 0\\ -1.05 & 0.0249 & -0.4629 & 2.4849 & 0\\ 0 & 0.0996 & -0.0996 & -0.0415 & 0\\ 0 & -10^{-6} & 10^{-6} & -0.0001 & 0\end{bmatrix}$$

$$[B_1,\ B_2,\ B_3,\ B_4,\ B_5,\ B_6,\ B_7,\ B_8]= \qquad (27)$$

$$10^6\times\begin{bmatrix}1.4547 & 1.4547 & 0.6061 & 0.6061 & 1.8184 & 1.8184 & 0.9698 & 0.9698\\ 3.3264 & 3.3264 & 3.3391 & 3.3291 & 3.3264 & 3.3264 & 3.3291 & 3.3291\\ 2.6518 & 0.8821 & 2.6518 & 0.8821 & 2.6464 & 0.8767 & 2.6464 & 0.8767\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}$$

Based on the LMI of (24), the state feedback control gain via LMI toolbox of Matlab[13] with $D=diag\{50,10,10,100,50\}$ are obtained as follows:

$$\begin{aligned}
K_1&=[0.0016,\ 0.0050,\ 0.0039,\ 0.0753,\ -180.9313],\\
K_2&=[0.0018,\ 0.0055,\ 0.0041,\ 0.0834,\ -200.0407],\\
K_3&=[0.0018,\ 0.0053,\ 0.0041,\ 0.0795,\ -190.8994],\\
K_4&=[0.0020,\ 0.0058,\ 0.0044,\ 0.0897,\ -215.2376],\\
K_5&=[0.0016,\ 0.0049,\ 0.0037,\ 0.0727,\ -174.6668],\\
K_6&=[0.0018,\ 0.0053,\ 0.0039,\ 0.0803,\ -192.7295],\\
K_7&=[0.0017,\ 0.0052,\ 0.0040,\ 0.0782,\ -187.9577],\\
K_8&=[0.0019,\ 0.0057,\ 0.0043,\ 0.0870,\ -208.7686].
\end{aligned} \qquad (28)$$

Simulation results carried out with PSIM[13] for the designed TS integral fuzzy controller are shown in Fig. 2 (a), (b), (c) and (d). Here, the load resistance changed from 2.4 [Ω] to 0.8 [Ω]at 6ms and back to 2.4 [Ω] at 10ms. Fig.2 (c) and (d) have the same load changes as Fig. 2 (a) and (b) except 20% parameter error of inductor L_1. From the figure, one can see that the TS fuzzy integral controller regulates the output voltage V_o at 48[V] smoothly in 2[ms] as the inductor current i_{L1} changes to the values required by the load.

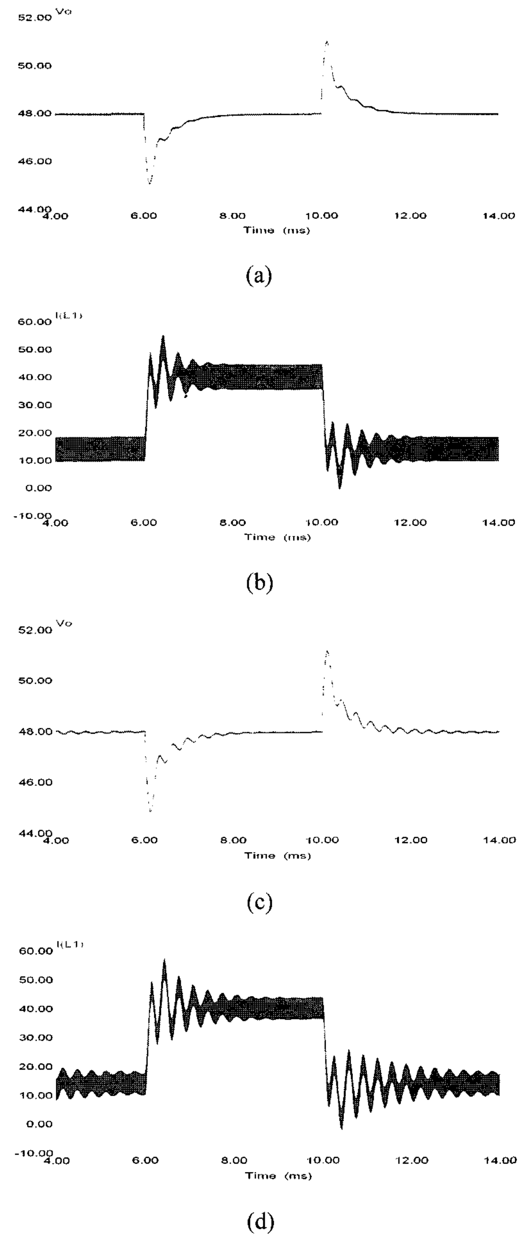

Fig. 2 Output voltages of the current doubler rectified asymmetric half-bridge DC/DC converter with the TS-Fuzzy integral controller considered in this paper. (a) V_o , (b) I_{L1}, (c) V_o, (d) I_{L1}: (c) and (d) are for the case of 20% parameter error of inductor L_1.

For the purpose of the comparison, simulation results of the type 2 error amplifier [12] designed with R_1=4[kΩ], R_2=10[kΩ], C_1=50[nF] and C_2=100[pF] via the conventional loop-gain method are shown in Fig. 3 (a) , (b), (c) and (d). As can be observed, the output voltage variation of the TS-Fuzzy integral controller is smaller in magnitude and shorter in progress than that of the conventional feedback controller.

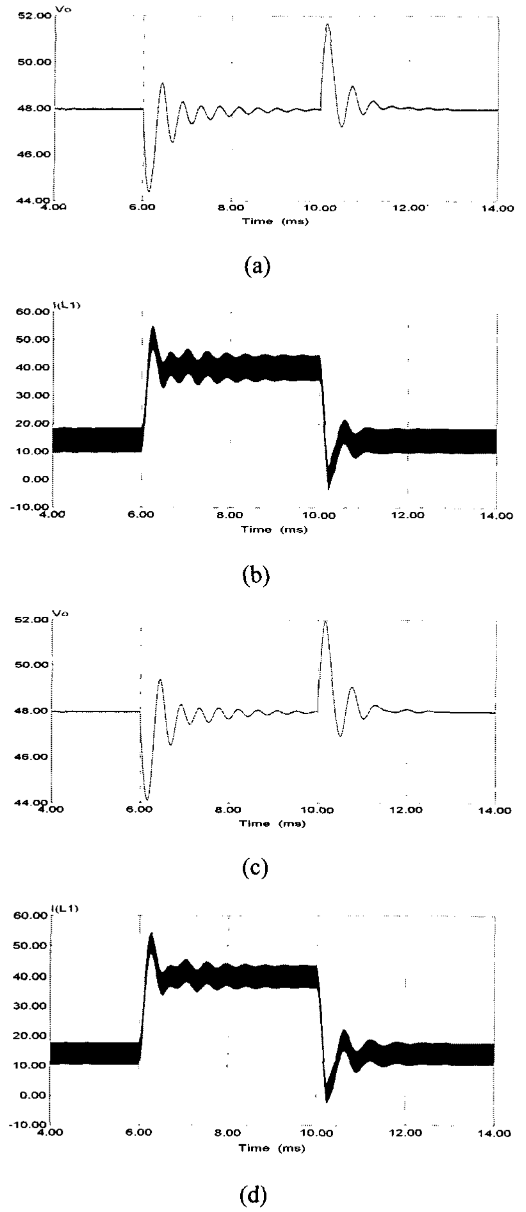

Fig. 3 Output voltages of the current doubler rectified asymmetric half-bridge DC/DC converter with the type-2 controller designed with the conventional design method. (a) V_o , (b) I_{L1}, (c) V_o, (d) I_{L1}: (c) and (d) are for the case of 20% parameter error of inductor L_1

5. Conclusion

In this paper, the TS fuzzy integral control approach proposed by Lian et al.[5] is applied to the regulation of the output voltage of the CRDAHB DC/DC converter. After modeling the dynamic characteristics of the CRDAHB DC/DC converter with state-space averaging method and additionally introducing the integral state of the output regulation error, we obtained the TS fuzzy model for the augmented system in the new coordinate centered in equilibrium points. The concept of the parallel distributed compensation was employed, and the state feedback gains of the TS fuzzy integral controller were obtained by solving the linear matrix inequalities (LMIs). Since LMIs can be solved efficiently within a given tolerance by the interior point methods, the LMI-based design is quite effective in practice. Simulations in the time-domain utilizing PSIM program showed that the performance of the designed TS fuzzy integral controller is satisfactory when it is compared to that of the conventional feedback controller.

Further investigations yet to be done will include the experimental verification and theoretical extension of the considered method toward the use of piecewise quadratic Lyapunov functions.

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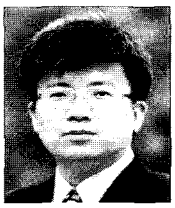

Gyo-Bum Chung was born in Seoul, Korea, in 1959. He received B.S. and M.S. degrees in electrical engineering from Seoul National University, in 1983 and 1985, respectively, and a Ph.D. degree in Electrical Engineering from the University of Florida, Gainesville, FL, USA, in 1992. He was a research associate at VPI & SU, Blacksburg, VA, USA, from 1992 to 1993. He was a senior researcher for the Electric Vehicle Development Team at the Korea Electro-Technology Research Institute from 1993 to 1994. Since 1995, he has been a professor with the Department of Electronic and Electrical Engineering, Hongik University. His research interests are in the areas of power electronics; the design of power converters, power quality, FACTS and advanced control of electrical machines. Prof. Chung is a member of the Korean Institute of Power Electronics.

Sun-Geun Kwack was born in Seoul, Korea, in 1977. He received an associate degree in the electrical engineering at Daelim College, Anyang, Korea. He received his B.S. degree from the KEDI educational system. He had worked with PSD tech. for 3 years, where he was a researcher for arc fault circuit interrupters and power quality. He is currently working toward his M.S. degree in Hongik University. His research interests are power electronic and power quality. He is a member of the Korean Institute of Power Electronics.