Takagi-Sugeno Fuzzy Integral Control for Asymmetric Half-Bridge DC/DC Converter

Gyo-Bum Chung

Dept. of Electronic and Electrical Eng., Hongik University, Jochiwon, Chungnam, 339-701, Korea

Abstract

In this paper, Takagi-Sugeno (TS) fuzzy integral control is investigated to regulate the output voltage of an asymmetric half-bridge (AHB) DC/DC converter; First, we model the dynamic characteristics of the AHB DC/DC converter with state-space averaging method and small perturbation at an operating point. After introducing an additional integral state of the output regulation error, we obtain the 5^{th}-order TS fuzzy model of the AHB DC/DC converter. Second, the concept of the parallel distributed compensation is applied to design the fuzzy integral controller, in which the state feedback gains are obtained by solving the linear matrix inequalities (LMIs). Finally, simulation results are presented to show the performance of the considered design method as the output voltage regulator and compared to the results for which the conventional loop gain method is used.

Keywords: Asymmetric Half Bridge DC/DC converter, State-Space Averaging Method, Takagi-Sugeno Fuzzy Model, Integral Control, Regulation, Linear Matrix Inequality

1. Introduction

Recently, with rapid progress made in power semi-conductor applications, the needs for high-performance control have dramatically increased in the area. 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 AHB (asymmetric half-bridge) DC/DC converter[1,2], boost converter[3,4], and buck converter[5,6]. Among the results, the TS (Takagi-Sugeno) fuzzy integral control approach which is 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 AHB DC/DC converter.

The AHB DC/DC converter has been known to have many advantages in the area of the power conversion because the topology of the converter is relatively simple and the voltage ratings of the switching devices are reduced[1,2]. Due to the nonlinear characteristics of the converter DC gain, maintaining its output voltage constant regardless of the output load changes has been known to be a difficult task, which degrades the overall performance of the AHB DC/DC converter[2].

The remaining parts of this paper are organized as follows: Section 2 presents the modeling process for the AHB DC/DC converter. The "output to duty cycle" transfer function considering the integral state of the output error is presented. Section 3 describes how to apply the integral TS fuzzy control to the output regulation of the converter. In Sections 4, simulation results are compared to those obtained with the conventional loop gain method in order to evaluate the performance of the TS fuzzy integral control. Finally, concluding remarks are given in Section 5. A preliminary conference version of this paper is to appear in [13].

Manuscript received Mar. 1, 2007; revised Mar. 13, 2007.
† Corresponding Author: gbchung@wow.hongik.ac.kr
Tel: +82-41-860-2595, Fax: +82-41-863-7605, Hongik Univ.

2. Modeling of Asymmetric Half-Bridge DC/DC Converter

Fig. 1 shows the AHB DC/DC converter with 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_0 is the number of turns on the primary winding of transformer T_X. N_1 and N_2 are the numbers of turns on the secondary windings.

For the analysis of the converter operation, the parasitic resistances of inductor and capacitors are considered, which are R_F, R_i and R_C.

It is assumed that $n_1 = N_1/N_0 = n_2 = N_2/N_0 = n$. However, the dead time between S_1 and S_2, the leakage inductance of transformer T_X, and the diode voltage drop are neglected.

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

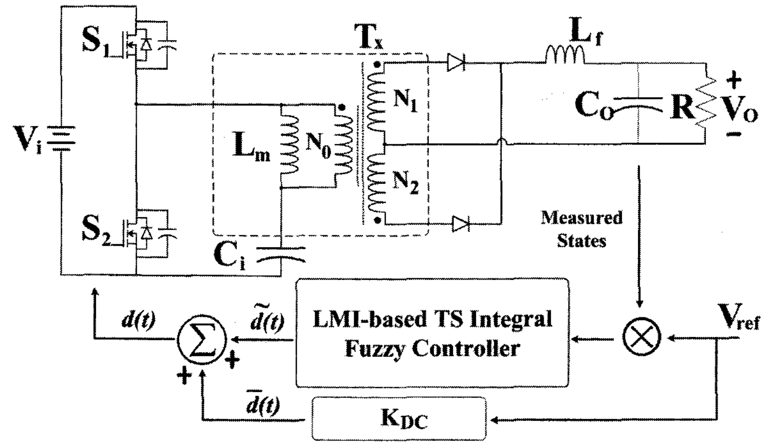


Fig. 1 Diagram of Asymmetric Half Bridge DC/DC converter System

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

where

$$x^T = [v_{ci} \quad i_{Lm} \quad i_{LF} \quad v_{co}]$$

$$A_1 = \begin{bmatrix} 0 & 1/C_i & n_1/C_i & 0 \\ -1/L_m & -R_i/L_m & -R_i \cdot n_1/L_m & 0 \\ -n_1/L_F & -n_1 \cdot R_i/L_F & a_{33}/L_F & -a_{34}/L_F \\ 0 & 0 & a_{34}/C_o & -a_{44}/C_o \end{bmatrix} \qquad (2)$$

$$a_{33} = -\left[n_1^2 \cdot R_i + R_C \cdot R/(R_C + R) + R_F\right]$$
$$a_{34} = R/(R_C + R)$$
$$a_{44} = 1/(R_C + R)$$
$$B_1^T = [0 \quad 1/L_m \quad n_1/L_F \quad 0]$$
$$C_1 = [0 \quad 0 \quad (R_C \cdot a_{34}) \quad a_{34}]$$

When switch S1 is off and switch S2 is on for $(1-D)T \le t \le T$, the AHB DC/DC converter in Fig. 1 can be expressed as

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

where

$$A_2 = \begin{bmatrix} 0 & 1/C_i & -n_2/C_i & 0 \\ -1/L_m & -R_i/L_m & R_i \cdot n_2/L_m & 0 \\ n_2/L_F & n_2 \cdot R_i/L_F & a_{2,33}/L_F & -a_{34}/L_F \\ 0 & 0 & a_{34}/C_o & -a_{44}/C_o \end{bmatrix} \qquad (4)$$

$$a_{2,33} = -\left[n_2^2 \cdot R_i + R_C \cdot R/(R_C + R) + R_F\right]$$
$$B_2^T = [0 \quad 0 \quad 0 \quad 0]$$
$$C_2 = [0 \quad 0 \quad R_C \cdot a_{34} \quad a_{34}]$$

The state-space-averaged model[1,2] of the AHB DC/DC converter at an operating point can be written as follows:

$$\dot{x} = A_a \cdot x + B_a \cdot V_i$$
$$y = C_a \cdot x \qquad (5)$$

where

$$A_a = d \cdot A_1 + (1-d) \cdot A_2$$
$$= \begin{bmatrix} 0 & 1/C_i & (2d-1) \cdot n/C_i & 0 \\ -1/L_m & -R_i/L_m & -(2d-1) \cdot R_i \cdot n/L_m & 0 \\ -(2d-1) \cdot n/L_F & -(2d-1) \cdot n \cdot R_i/L_F + & a_{2,33}/L_F & -a_{34}/L_F \\ 0 & 0 & a_{34}/C_o & -a_{44}/C_o \end{bmatrix} \qquad (6)$$

$$B_a = d \cdot B_1 + (1-d) \cdot B_2 = [0 \quad d/L_m \quad n_1 \cdot d/L_F \quad 0]^T$$
$$C_a = d \cdot C_1 + (1-d) \cdot C_2 = [0 \quad 0 \quad R_C \cdot a_{34} \quad a_{34}]$$

Since $\dot{x} = 0 = A_a \cdot x + B_a \cdot V_i$ in steady state, we can find voltages and currents of the converter at the steady-state operating point: $\overline{x} = -A_a^{-1} \cdot B_a \cdot V_i$ and $\overline{y} = C_a \cdot \overline{x}$.

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

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

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

$$\dot{\tilde{x}} = A_s \cdot \tilde{x} + B_s \cdot \tilde{d} + E_s \cdot \tilde{v}_i \qquad (8)$$
$$\tilde{y} = C_s \cdot \tilde{x}$$

where

$$A_s=\begin{bmatrix} 0 & 1/C_i & (2D-1)\cdot n/C_i & 0 \\ -1/L_m & -R_i/L_m & -(2D-1)\cdot R_i\cdot n/L_m & 0 \\ -(2D-1)\cdot n/L_F & -(2D-1)\cdot n\cdot R_i/L_F & a_{233}/L_F & -a_{34}/L_F \\ 0 & 0 & a_{34}/C_o & -a_{44}/C_o \end{bmatrix}$$

$$B_s=\begin{bmatrix} 2n\left(I_{LF}+\tilde{i}_{Lf}\right)/C_i \\ \left[-2nR_i\left(I_{LF}+\tilde{i}_{Lf}\right)+V_i\right]/L_m \\ -n\left[2\left(V_{Ci}+\tilde{v}_{Ci}\right)+2R_i\left(I_{LM}+\tilde{i}_{LM}\right)-V_i\right]/L_F \\ 0 \end{bmatrix} \tag{9}$$

$$E_s^T=\begin{bmatrix}0 & D/L_m & n\cdot D/L_F & 0\end{bmatrix}$$

$$C_s=\begin{bmatrix}0 & 0 & R_C\cdot a_{34} & a_{34}\end{bmatrix}$$

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. The small-signal ac dynamic model of the converter added with the error state is rewritten as follows:

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

where

$$\tilde{x}^T=\begin{bmatrix}v_{ci} & i_{Lm} & i_{LF} & v_{co} & x_e\end{bmatrix}$$

$$A_x=\begin{bmatrix} 0 & 1/C_i & (2D-1)\cdot n_1/C_i & 0 & 0 \\ -1/L_m & -R_i/L_m & -(2D-1)\cdot R_i n_1/L_m & 0 & 0 \\ -(2D-1)\cdot n_1/L_F & -(2D-1)\cdot n_1\cdot R_i/L_F & a_{233}/L_F & -a_{34}/L_F & 0 \\ 0 & 0 & a_{34}/C_o & -a_{44}/C_o & 0 \\ 0 & 0 & -R_C\cdot a_{34} & -a_{34} & 0 \end{bmatrix}$$

$$B_x=\begin{bmatrix} 2n_1\left(I_{LF}+\tilde{i}_{Lf}\right)/C_i \\ \left[-2n_1R_i\left(I_{LF}+\tilde{i}_{Lf}\right)+V_i\right]/L_m \\ -n_1\left[2\left(V_{Ci}+\tilde{v}_{Ci}\right)+2R_i\left(I_{Lm}+\tilde{i}_{Lm}\right)-V_i\right]/L_F \\ 0 \\ 0 \end{bmatrix} \tag{11}$$

$$E_x^T=\begin{bmatrix}0 & \bar{d}/L_m & n\cdot\bar{d}/L_F & 0 & 0\end{bmatrix}$$

$$C_x=\begin{bmatrix}0 & 0 & R_C\cdot a_{34} & a_{34} & 0\end{bmatrix}$$

Now controller design methods such as the conventional loop gain method, LQG control, H∞ control or fuzzy control can be applied to the state-space representations (8) or (9). In this paper, TS fuzzy control approach with (10) is considered in the next section.

3. Theoretical Aspects on Fuzzy Controller Design Utilizing LMIs

This section addresses the problem of applying an integral TS fuzzy control approach to regulating the AHB DC/DC converter. Here, we follow the strategy of Lian et al.[5] to design the fuzzy controller, and details on the approach of this paper have also appeared in the preliminary conference version paper[13]. 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. Then, the standard TS fuzzy model is established with the new coordinates centered at the regulated points. Finally, the concept of parallel distributed compensation (PDC) is applied to design TS fuzzy controller, in which the state feedback gains are obtained by solving LMIs[9] via MATLAB. The MATLAB program for obtaining the state feedback gains consists of the part specifying the TS fuzzy model of the considered converter system along with the LMI solver part dealing with the LMI variables declaration and LMI equations description. 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 can be represented by the following general class of nonlinear systems:

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

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, which belongs to the integral-type controllers, thus can not only achieve zero steady-state regulation error but also be robust to 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, i.e.,

$$x_e(t)=\int_0^t((r-y(\tau))d\tau+x_e(0) \tag{13}$$

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

$$\dot{x}_p(t)=f\left(x_p(t),d(t)\right)$$
$$\dot{x}_e(t)=r-h\left(x_p(t)\right) \tag{14}$$

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

$$f\left(\bar{x}_p,\bar{d}\right)=0$$
$$r-h\left(\bar{x}_p\right)=0 \tag{15}$$

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 point $\bar{x}_p$, $\bar{d}$ 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_0 and h_0, satisfy $f_0(0,0)=0$ and $h_0(0)=0$, respectively. From the model of the modeling results of the previous section, it is observed that the augmented system (16) for the AHB DC/DC converter can be represented by the TS fuzzy model, in which the i-th rule has the rule of the following form:

Plant Rule i:
IF $z_1(t)$ is F_1^i and $\cdots$ $z_g(t)$ is F_g^i,
THEN $\dot{\tilde{x}}(t)=A_i\cdot\tilde{x}(t)+B_i\cdot\tilde{d}(t)$, (17)

where $i=1,\cdots,m$. Here, $\tilde{x}(t)=[\tilde{x}_p^T(t)\ \ \tilde{x}_e(t)]^T$ 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 based on the product inference, 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
$\mu_i(x_p(t))=w_i(x_p(t))/\sum_i w_i(x_p(t))$ with
$w_i(x_p(t))=\prod_{j=1}^{g}F_j^i(x_p(t))$ 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, we will denote the normalized weight function $\mu_i(x_p(t))$ 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:
IF $z_1(t)$ is F_1^i and $\cdots$ $z_g(t)$ is F_g^i,
THEN $\tilde{d}(t)=-K_i\tilde{x}(t)$ (21)

where $l=1,\cdots,m$. 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]

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

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

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

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]. Note that the strategy of using the results of Theorem 2.2 of [10] only without utilizing Theorem 1 of [5] could suffer from the possibility of the designed local state feedback gains K_i becoming quite similar each other.

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:

$$\begin{aligned}&N_{ii}(Y)<0, i=1,\cdots,m\\ &\frac{1}{m-1}N_{ii}(Y)+\frac{1}{2}(N_{ij}(Y)+N_{ji}(Y))<0, \qquad 1\leq i\neq j\leq n\end{aligned} \tag{24}$$

where

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

As mentioned before, the LMI problems stated in the above theorem are, here in this paper, solved utilizing the MATLAB LMI Control Toolbox[14]. For this, we first define the LMI variables X, and $M_1,\cdots,M_m$ using the function "lmivar", then specifies the LMIs (24) using the function "lmiterm", and finally find solutions for the LMI variables using the function "feasp". After the LMI variables are obtained, the local state feedback gains K_j are computed by use of the change of variables formula $K_j=M_jX^{1}$.

4. Design Example and Simulation

In this section, we present an example of the TS fuzzy control approach described above, which deals with the problem of regulating the output voltage of the AHB DC/DC converter. Numerical simulations with PSIM[11] are carried out to show the performance of the integral TS fuzzy controller to regulate the output voltage V_o. We consider the converter with the system parameters of Table 1[1]. Its equilibrium points satisfying (15) are as follows: $\bar{x}_p=[\bar{v}_{ci}\ \ \bar{i}_{Lm}\ \ \bar{i}_{LF}\ \ \bar{v}_{co}]^T$ $=[90,\ \ 0.4103,\ \ 6.838,\ \ 17.78]$ and $\bar{d}=0.3$.

Table 1. Parameters of the the asymmetric half-bridge DC/DC converter[7].

Parameters	Value	Unit
Input Voltage, V_i	300	V
Input Capacitor, C_i	0.82	μF
Parasitic Resistance for C_i, R_i	0.74	Ω
Magnetizing Inductance, L_m	198	μH
Output Inductance, L_F	18	μH
Parasitic Resistance for L_F, R_F	0.15	Ω
Output Capacitance, C_O	880	μF
Parasitic Resistance for C_O, R_o	0.025	Ω
Output Resistance, R	2.6	Ω
Transformer Turn Ratio ($1:n_1$), $n_1 = n_2$	0.15	
Switching Frequency, f_s	100	kHz
Nominal output voltage, V_o	17.78	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}=90, h_{Lm}=0.4 and h_{LF}=6.5, the membership functions of (17) are defined as follows:

$$
\begin{aligned}
&F_1^1(\tilde{v}_{ci}) = F_1^2(\tilde{v}_{ci}) = F_1^3(\tilde{v}_{ci}) = F_1^4(\tilde{v}_{ci}) = \frac{1}{2}\left[1 + \frac{\tilde{v}_{ci}(t)}{h_{ci}}\right] \\
&F_1^5(\tilde{v}_{ci}) = F_1^6(\tilde{v}_{ci}) = F_1^7(\tilde{v}_{ci}) = F_1^8(\tilde{v}_{ci}) = \frac{1}{2}\left[1 - \frac{\tilde{v}_{ci}(t)}{h_{ci}}\right] \\
&F_2^1(\tilde{i}_{Lm}) = F_2^2(\tilde{i}_{Lm}) = F_2^5(\tilde{i}_{Lm}) = F_2^6(\tilde{i}_{Lm}) = \frac{1}{2}\left[1 + \frac{\tilde{i}_{Lm}(t)}{h_{Lm}}\right] \\
&F_2^3(\tilde{i}_{Lm}) = F_2^4(\tilde{i}_{Lm}) = F_2^7(\tilde{i}_{Lm}) = F_2^8(\tilde{i}_{Lm}) = \frac{1}{2}\left[1 - \frac{\tilde{i}_{Lm}(t)}{h_{Lm}}\right] \\
&F_2^2(\tilde{i}_{LF}) = F_2^4(\tilde{i}_{LF}) = F_2^6(\tilde{i}_{LF}) = F_2^8(\tilde{i}_{LF}) = \frac{1}{2}\left[1 - \frac{\tilde{i}_{LF}(t)}{h_{LF}}\right] \\
&F_3^1(\tilde{i}_{LF}) = F_3^3(\tilde{i}_{LF}) = F_3^5(\tilde{i}_{LF}) = F_3^7(\tilde{i}_{LF}) = \frac{1}{2}\left[1 + \frac{\tilde{i}_{LF}(t)}{h_{LF}}\right]
\end{aligned}
\qquad (26)
$$

Also, the resultant local models $(A_i,\ B_i)$, i=1,…,8 obtained by plugging the parameter values of Table 1 into (9) are as follows:

$$
A_1 = \cdots = A_8
= 10^6 \times \begin{bmatrix} 0 & 1.2195 & -0.0732 & 0 & 0 \\ -0.0051 & -0.0037 & 0.0002 & 0 & 0 \\ 0.0033 & 0.0025 & -0.0094 & -0.0555 & 0 \\ 0 & 0 & 0.0011 & -0.0004 & 0 \\ 0 & 0 & -0.0025\times10^{-6} & -0.9990\times10^{-6} & 0 \end{bmatrix} \qquad (27)
$$

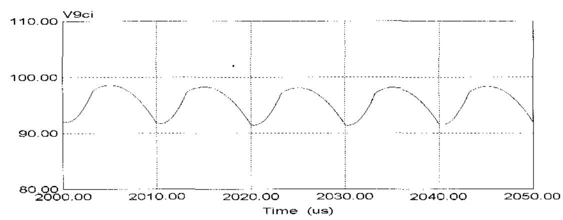
$$
[B_1,\ B_2,\ B_3,\ B_4] = 10^6 \times \begin{bmatrix} 4.8797 & 4.8797 & 4.8797 & 4.8797 \\ 1.5002 & 1.5002 & 1.5002 & 1.5002 \\ 0.5100 & 2.4900 & -0.5001 & 2.4999 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
$$

$$
[B_5,\ B_6,\ B_7,\ B_8] = 10^6 \times \begin{bmatrix} 0.1236 & 0.1236 & 0.1236 & 0.1236 \\ 1.5148 & 1.5148 & 1.5148 & 1.5148 \\ -0.5100 & 2.4900 & -0.5001 & 2.4999 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
$$

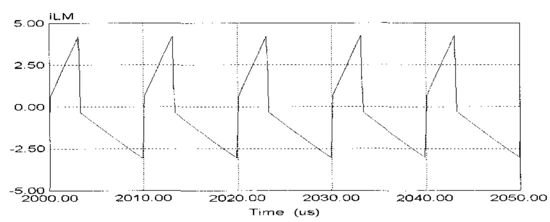
Based on the LMI of (24), the state feedback control gains via LMI toolbox of Matlab[13] with $D = diag\{10, 10, 10, 10, 50\}$ are obtained as follows:

K_1=[0.02386e-4, 0.0054, 0.0036,0.0396, -268.8969],
K_2=[0.03833e-4,0.0058, 0.0053, 0.0545, -369.2316],
K_3=[0.02401e-4,0.0054, 0.0036, 0.0398, -269.7915],
K_4=[0.03835e-4,0.0058, 0.0053, 0.0545, -369.3647], (28)
K_5=[0.09515e-4,0.0097, 0.0094, 0.1013, -688.1066],
K_6=[0.06832e-4,0.0105, 0.0094, 0.0969, -656.6777],
K_7=[0.09184e-4,0.0099, 0.0093, 0.1003, -681.6786],
K_8=[0.06828e-4,0.0105, 0.0094, 0.0969, -656.4851].

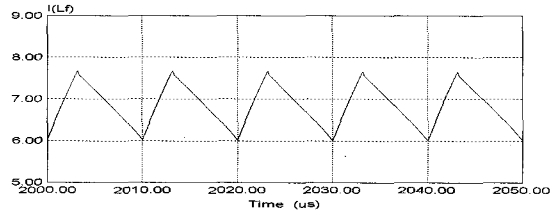
Simulation results are carried out with PSIM[11] for the designed TS integral fuzzy controller. Fig 2 shows the 5-cycle waveforms of the AHB DC/DC converter at the equilibrium point satisfying (15), which are the voltage of C_i, the currents of L_m and L_F, and the output voltage. The waveforms of the voltages and currents at the steady state condition show the asymmetric characteristics and the complementary switching of the converter.



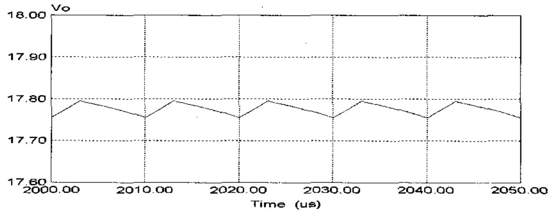
(a)



(b)



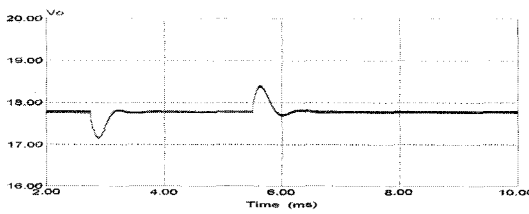
(c)



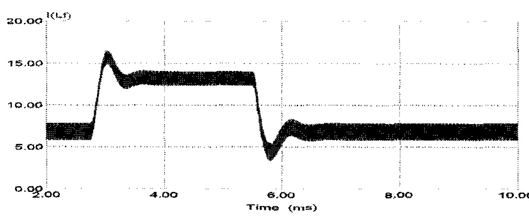
(d)

Fig. 2. Instantaneous 5-cycle waveforms of the asymmetric half-bridge DC/DC converter with the TS-Fuzzy integral controller considered in this paper. (a) VCi , (b) ILm, (c) ILF, (d) Vo

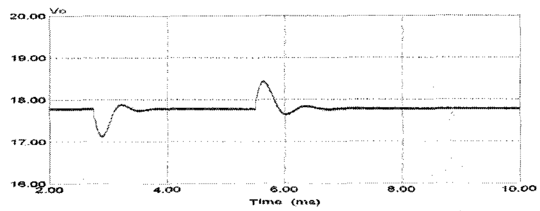
Simulation results for transients are shown in Fig. 3. In Fig. 3 (a) and (b), the load resistance changed from the initial value of 2.6 [Ω] to 1.3 [Ω]at 2.75[ms] and back to 2.4 [Ω] at 5.5[ms]. Fig.2 (c) and (d) have the same load changes as Fig. 3 (a) and (b) except 20% increased inductance of L_F. Fig.3 (e) and (f) are the load regulation for step changes of the input voltage V_i from 300[V] to 315[V] at 2.75[ms] and back to 300[V] at 5.5[ms]. From the waveforms of the figure, one can see that the TS fuzzy integral controller regulates the output voltage V_o at 17.78[V] effectively as the inductor current I_{L1} changes to the values required by the load.



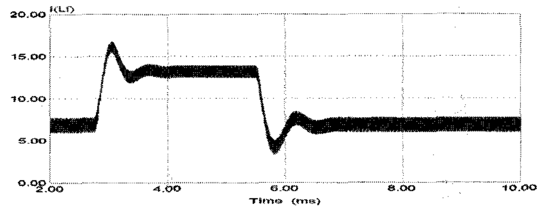
(a)



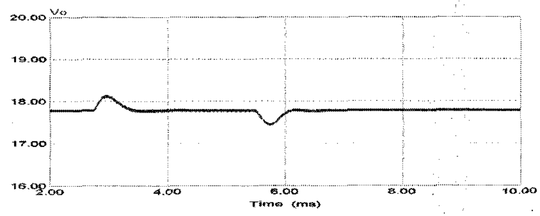
(b)



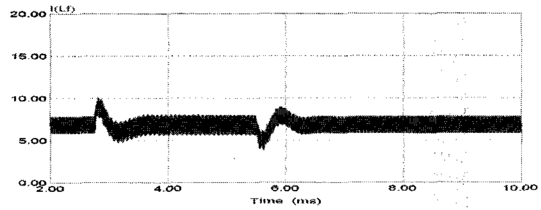
(c)



(d)



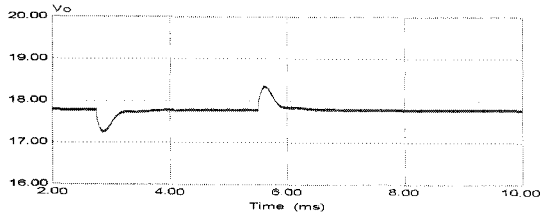
(e)



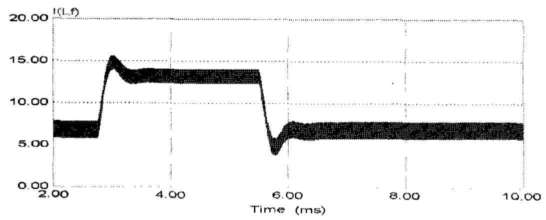
(f)

Fig. 3. Waveforms of the asymmetric half-bridge DC/DC converter with the TS-Fuzzy integral controller considered in this paper. (a) Vo , (b) ILF, (c) Vo , (d) ILF, (e) Vo, (f) ILF: (a) and (b) are the load regulation for the 50% step changes of the load R. (c) and (d) are for the case of 20% parameter error of inductor LF. (e) and (f) are the line regulation for 5% step changes of input voltage Vi.

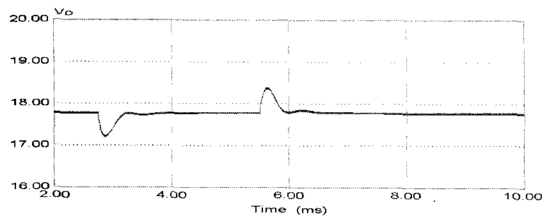
For the purpose of the comparison, simulation results of the type 2 error amplifier [12] designed with R_1=4.7[kΩ], R_2=23.5[kΩ], C_1=10[nF] and C_2=100[pF] via the conventional loop-gain method applied to (8) in Section 2 are shown in Fig. 4. As can be seen, the outputs of the TS fuzzy integral controller are comparable in terms of magnitude and duration to those obtained with the conventional loop gain controller.



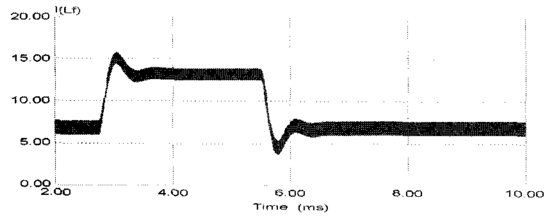
(a)



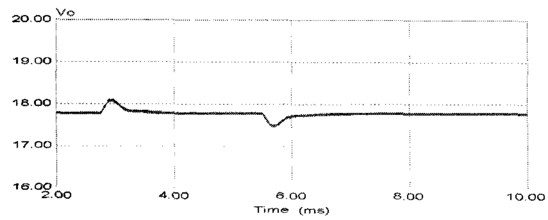
(b)



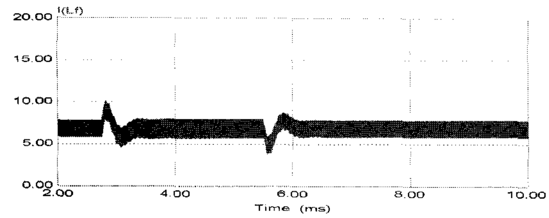
(c)



(d)



(e)



(f)

Fig. 4. Waveforms of the asymmetric half-bridge DC/DC converter with type-2 controller with the conventional design method. (a) Vo , (b) ILF, (c) Vo , (d) ILF, (e) Vo, (f) ILF: (a) and (b) are the load regulation for the 50% step changes of the load R. (c) and (d) are for the case of 20% parameter error of inductor LF. (e) and (f) are the line regulation for 5% step changes of input voltage Vi.

5. Conclusions

In this paper, TS fuzzy integral control is applied to the regulation of the output voltage of an asymmetric half-bridge (AHB) DC/DC converter. First, we model the dynamic characteristics of the AHB DC/DC converter with state-space averaging method, and after introducing an additional integral state of the output regulation error, we obtain the Takagi-Sugeno (TS) fuzzy model of the 5th order augmented system. Second, the concept of the parallel distributed compensation is applied to design the fuzzy integral controller, in which the state feedback gains are obtained by solving the linear matrix inequalities (LMIs). Finally, simulations in time-domain with PSIM program are presented to show that the performance of the considered design method is comparable to that of the conventional loop gain method with the type-2 controller when it is necessary to regulate the output voltage effectively for the cases of steady state and transients; the load variation, the converter parameter error, and the input voltage change.

References

[1] J.H. Park, M.R. Zolghadri, B. Kimiaghalam, A. Homaifar, F.C. Lee, "LQG Controller for asymmetrical half-bridge converter with range winding," In Proceedings of 2004 IEEE International Symposium on Industrial Electronics (2004) pp. 1261- 1265.

[2] L. Yao, J. Abu-Qahouq, and I. Batarseh, 'Unified Analog abd Digital models for Half Bridge DC-DC Converter with Current Doubler Rectifier," Proceedings of IEEE APEC2005, pp. 1386-1392, 2005.

[3] H.K. Lam, T.H. Lee, F.H.F. Leung, P.K.S. Tam, "Fuzzy control of DC_DC switching converters: stability and robustness analysis," In Proceedings of 27th Annual Conf. of the IEEE Industrial Electronics, pp.1261-1265, 2004.

[4] R. Naim, G. Weiss, S. Ben-Yaakov, "H^{∞}control applied to boost power converters," IEEE Transactions on Power Electronics, Vol. 12, pp 677 - 683, 1997.

[5] K.-Y. Lian, J.-J. Liou, and C.-Y. Huang, "LMI-based integral fuzzy control of DC-DC converters," IEEE Transactions on Fuzzy Systems. Vol. 14, No. 1, pp. 71-80, 2006.

[6] T.-S. Chiang, C.-S. Chiu, and P. Liu, "Robust fuzzy integral regulator design for a class of affine nonlinear systems," IEICE Transactions on Fundamentals, Vol. E89-A, No.4, pp. 1100-1107, 2006.

[7] S. Korotkov, V. Meleshin, A. Nemchinov, and S. Fraidlin, "Small-signal modeling of soft-switched asymmetrical half-bridge DC/DC converter," Proceedings of IEEE APEC95, pp. 707-711, 1995.

[8] K. Tanaka and H. O. Wang, Fuzzy Control Systems Design and Analysis: A Linear Matrix Inequalities Approach, John Wiley & Sons, New York, 2001.

[9] S. Boyd, L. El Ghaoui, E. Feron, and V. Balakrishnan, Linear Matrix Inequalities in Systems and Control Theory, SIAM Studies in Applied Mathematics, vol. 15, SIAM, Philadelphia, 1994.

[10] H. D. Tuan, P. Apkarian, T. Narikiyo, and Y. Yamamoto, "Parameterized linear matrix inequality techniques in fuzzy control system design," IEEE Transactions on Fuzzy Systems, Vol. 9, No.2, pp.324-332, 2001.

[11] http://www.powersimtech.com/manual/psim-manual.pdf, PSIM User Manual, Powersim Inc., 2006.

[12] Abraham I. Pressman, Switching Power Supply Design, 2nd Edition, McGRAW-HILL, New York, 1998.

[13] G.-B. Chung, "Application of fuzzy integral control for output regulation of asymmetric half-bridge DC/DC converter," To appear in Proceedings of International Conference on Adaptive and Natural Computing Algorithms, Warsaw, Poland, 2007.

[14] P. Gahinet, A. Nemirovskii, A.J. Laub, and M. Chilali, LMI Control Toolbox, Natick, MA: Mathworks, 1995.

Gyo-Bum Chung 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 with the Department of Electronic and Electrical Engineering, Hongik University, where he is currently an associate professor. His research interests are in the areas of power electronics; the design of power converters, power quality, FACTS and advanced control of electrical machines.