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Investigation of PID Fuzzy Controller for Output Voltage Regulation of Current-Doubler-Rectified Asymmetric Half-Bridge DC/DC Converter

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ABSTRACT

This paper investigates a PID fuzzy controller for output voltage regulation of a current-doubler-rectified asymmetric half-bridge (CDRAHB) DC/DC converter. The controller is a PD-type fuzzy controller in parallel with a linear integral controller. The PD type fuzzy controller is for providing the varying gain at the different operating conditions to regulate the output voltage. The linear integral controller is for removing the steady-state error of the output voltage. In order to show the outstanding dynamic characteristics of the proposed controller, PSIM simulation studies are carried out and compared to the results for which the conventional loop gain design method is used.

Keywords: Asymmetric Half-Bridge DC/DC Converter, Voltage Regulation, Current Doubler Rectification, State Space Averaging, Loop Gain, PID Fuzzy Controller

1. Introduction

The current-doubler-rectified asymmetric half-bridge (CDRAHB) DC/DC converter has been known to have many advantages in the area of the power conversion^[1,2]. However, 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. Recently, with rapid progress made in power semi-conductor applications, the needs for high-performance control have been dramatically increased in the area of power electronics. 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 CDRAHB DC/DC converter^[1,2], boost converter^[3,4], and buck converter^[5,6]. Among the results, the LMI-based TS (Takagi-Sugeno) fuzzy integral control approach^[5] turns out to be very promising, since it guarantees the stable output-regulation as well as the robustness and disturbance rejection capability^[7,8]. However, it requires the states observer for the feedback control and the precise modeling for calculating the feedback control gains.

Motivated by the recent studies of CDRAHB DC/DC converters^[1,2], this paper proposes a fuzzy-modified PID controller for the output-regulation of the CDRAHB DC/DC converter, which does not require the precise

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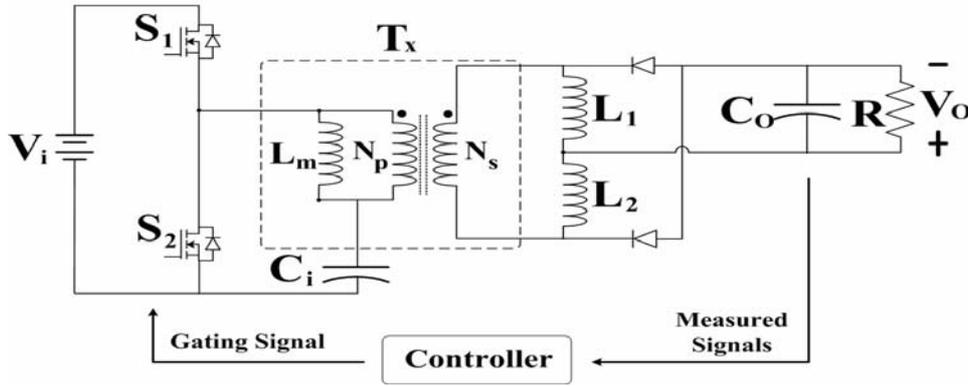


Fig. 1 Circuit diagram of current-doubler-rectified asymmetric half-bridge DC/DC converter

modeling of the CDRAHB DC/DC converter.

The remaining parts of this paper are organized as follows: Section 2 presents the modeling process for the CDRAHB DC/DC converter. Section 3 describes the PID fuzzy controller for the output voltage 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 DC/DC Converter

Fig. 1 shows the CDRAHB DC/DC converter with PID fuzzy 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.

For the analysis of the converter operation, the parasitic resistances of 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 $0 \leq t \leq dT$, the CDRAHB DC/DC converter in Fig.1 can be described by

$$\dot{x} = A_1 \cdot x + B_1 \cdot V_i \quad (1)$$

$$y = C_1 \cdot x$$

where

$$x^T = [v_{ci} \quad i_{L1} \quad i_{L2} \quad v_{co}],$$

$$A_1 = \begin{bmatrix} 0 & n/C_i & 0 & 0 \\ -n/L_1 & a_{221}/L_1 & R_{p1}/L_1 & -R_{p2}/L_1 \\ 0 & R_{p1}/L_2 & -(R_{L2}+R_{p1})/L_2 & R_{p2}/L_2 \\ 0 & R_{p2}/C_o & -R_{p2}/C_o & -1/(R_{Co}+R)/C_o \end{bmatrix} \quad (2)$$

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

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

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

$$B_1^T = [0 \quad n/L_1 \quad 0 \quad 0]$$

$$C_1 = [0 \quad R_{p1} \quad -R_{p1} \quad R_{p2}]$$

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

$$\dot{x} = A_2 \cdot x + B_2 \cdot V_i \quad (3)$$

$$y = C_2 \cdot x$$

where

$$A_2 = \begin{bmatrix} 0 & 0 & n/C_i & 0 \\ 0 & -(R_{L1}+R_{p1})/L_1 & R_{p1}/L_1 & -R_{p2}/L_1 \\ -n/L_2 & R_{p1}/L_2 & a_{332}/L_2 & R_{p2}/L_2 \\ 0 & R_{p2}/C_o & -R_{p2}/C_o & -1/(R_{Co}+R)/C_o \end{bmatrix} \quad (4)$$

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

$$B_2^T = [0 \quad 0 \quad 0 \quad 0]$$

$$C_2 = [0 \quad R_{p1} \quad -R_{p1} \quad R_{p2}]$$

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

$$\begin{aligned} \dot{x} &= A_a \cdot x + B_a \cdot V_i \\ &= [d \cdot A_1 + (1-d) \cdot A_2] \cdot x + [d \cdot B_1 + (1-d) \cdot B_2] \cdot V_i \end{aligned} \quad (5)$$

$$\begin{aligned} y &= C_a \cdot x \\ &= [d \cdot C_1 + (1-d) \cdot C_2] \cdot x \end{aligned}$$

where

$$A_a = \begin{bmatrix} 0 & d \cdot n / C_i & (1-d) \cdot n / C_i & 0 \\ -d \cdot n / L_1 & a_{22a} & R_{p1} / L_1 & -R_{p2} / L_1 \\ -(1-d) \cdot n / L_2 & R_{p1} / L_2 & a_{33a} & R_{p2} / L_2 \\ 0 & R_{p2} / C_o & -R_{p2} / C_o & -1 / (R_{C_o} + R) / C_o \end{bmatrix} \quad (6)$$

$$a_{22a} = -(R_{L1} + R_{p1} + d \cdot n \cdot n \cdot R_{C_i}) / L_1$$

$$a_{33a} = -(R_{L2} + R_{p1} + (1-d) \cdot n \cdot n \cdot R_{C_i}) / L_2$$

$$B_a^T = [0 \quad d \cdot n / L_1 \quad 0 \quad 0]$$

$$C_a = [0 \quad R_{p1} \quad -R_{p1} \quad R_{p2}]$$

Dynamic behavior of the converter can be described in terms of small signal variations around a steady-state operation point^[1,2,9]. The perturbed duty ratio, input voltage and states are represented as

$$\begin{aligned} x &= X + \tilde{x} \\ v_I &= V_I + \tilde{v}_i \\ d &= D + \tilde{d} \end{aligned} \quad (7)$$

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

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

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

where (9)

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

$$a_{22,s} = -(R_{L1} + R_{p1} + D \cdot n \cdot n \cdot R_{C_i}) / L_1$$

$$a_{33,s} = -(R_{L2} + R_{p1} + (1-D) \cdot n \cdot n \cdot R_{C_i}) / L_2$$

$$B_s = \begin{bmatrix} n(I_{L1} - I_{L2}) / C_i \\ -n[V_{C_i} - n \cdot R_{C_i} \cdot I_{L1} - V_i] / L_1 \\ n[V_{C_i} + n \cdot R_{C_i} \cdot I_{L2}] / L_1 \\ 0 \end{bmatrix}$$

$$E_s^T = [0 \quad nD \quad 0 \quad 0]$$

$$C_s = [0 \quad R_{p1} \quad -R_{p1} \quad R_{p2}]$$

The steady-state and dynamic characteristics of the CDRAHB DC/DC converter can be evaluated in (5) and (8), which are absolutely necessary for designing the output voltage controller with the conventional loop gain method^[13].

3. Design of PID Fuzzy Controller

Fig. 2 shows in detail the block diagram of the controller proposed in this paper. The controller consists of the fuzzy logic PD controller^[10] in parallel with a linear integral error amplifier.

For the fuzzy inference to regulate the output voltage

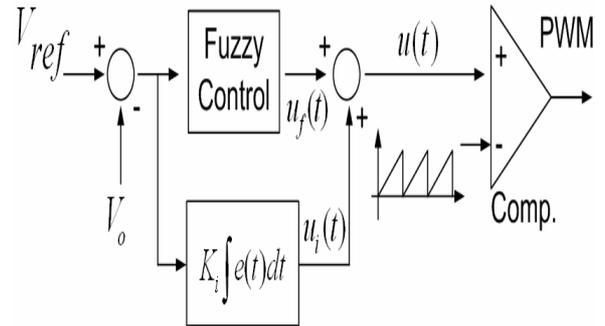


Fig. 2 Controller to generate the gating signal for the CDRAHB DC/DC converter

V_o , there are two input variables (the output voltage error $e(t)$ and the change of the error $ce(t)$) and the output variable (the duty ratio $u_f(t)$).

$$e(t) = V_{ref} - V_o \quad (10)$$

$$ce(t) = e(nT_s) - e((n-1)T_s) \quad (11)$$

The output voltage error as the first input (the IF) variable has the seven fuzzy subsets and the triangle membership function in Fig. 3.

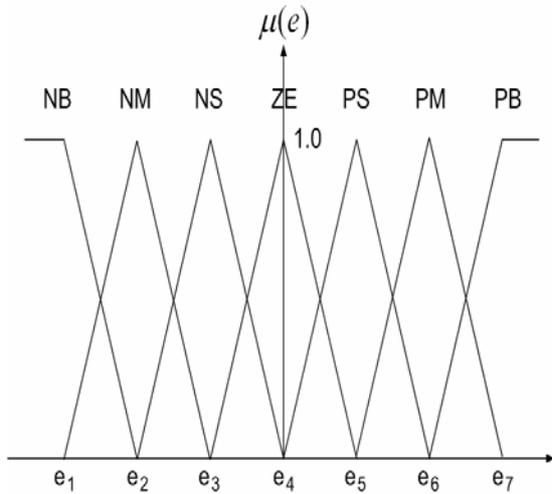


Fig. 3 Membership functions for error, $e(t)$

The change of the error as the second input variable has three fuzzy subsets and the triangle membership function in Fig. 4.

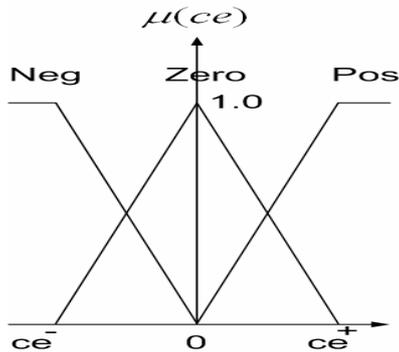


Fig. 4 Membership functions for the change of error, $ce(t)$.

The duty ratio as the output variable has nine fuzzy subsets and the triangle membership function in Fig. 5.

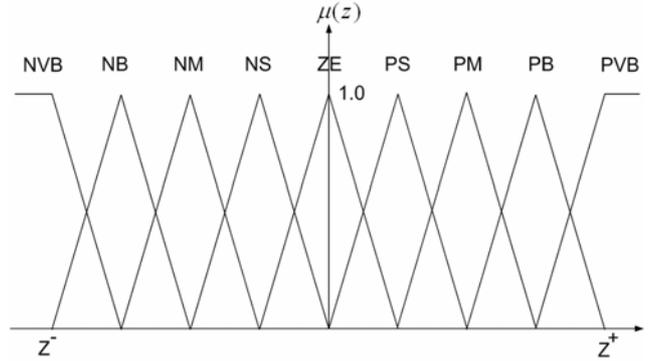


Fig.5 Output Membership Function for the duty

Table 1 shows the corresponding rule base for the output voltage regulation. The top row is for the fuzzy variable $e(t)$, the left column is for the fuzzy variable $ce(t)$, and the body of the matrix is the membership function of the output variable.

Table 1 Fuzzy rule base with 21 rules

$e(t)$ $Ce(t)$	<u>NV</u>	<u>NM</u>	<u>NS</u>	<u>ZE</u>	<u>PS</u>	<u>PM</u>	<u>PB</u>
<u>Neg</u>	<u>NVB</u>	<u>NB</u>	<u>NM</u>	<u>NS</u>	<u>ZE</u>	<u>PS</u>	<u>PM</u>
<u>Zero</u>	<u>NB</u>	<u>NM</u>	<u>NS</u>	<u>ZE</u>	<u>PS</u>	<u>PM</u>	<u>PB</u>
<u>Pos</u>	<u>NM</u>	<u>NS</u>	<u>ZE</u>	<u>PS</u>	<u>PM</u>	<u>PB</u>	<u>PVB</u>

The fuzzy rule base for the output voltage regulation has 21 rules of the following type:

Rule i : IF (the voltage error $e(t)$ is NS (negative small))
AND the change of the error $ce(t)$ is Neg (negative),
THEN the duty ratio is NM (negative medium).

where $i = 1, \dots, 21$.

In order to convert the fuzzy output to the crisp output u_f which is a part of the duty ratio, the height defuzzification method is used^[11]. The duty ratio obtained by the fuzzy inference can be obtained from

$$u_f = \frac{\sum_{i=1}^M \mu_o(z^i) \hat{z}^i}{\sum_{i=1}^M \mu_o(z^i)} \quad (12)$$

The magnitude of the duty for the output regulation of

the CDRAHB DC/DC converter is generated with the sum of the output u_i of the linear error integrator and the crisp output u_f inferred from the fuzzy logic with the output voltage error and the change of the error^[10].

4. Design Example and Simulation

In this section, we present an example of the PID fuzzy control approach described above applied to the problem of regulating the output voltage of the CDRAHB DC/DC converter. Numerical simulations with PSIM^[12] are carried out to show the performance of the proposed fuzzy controller and compared with the simulation results of the conventional loop-gain design method^[13]. We consider the converter with the system parameters of Table 2^[1], and its equilibrium points satisfying (5) with $\dot{x} = 0$ are as follows:

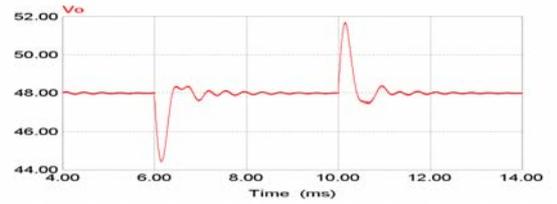
$$\bar{x}_p = [\bar{v}_{ci} \quad \bar{i}_{L1} \quad \bar{i}_{L2} \quad \bar{v}_{co}]^T = [117.97, 14.14, -6.06, 48.49]^T \quad \text{and} \\ \bar{d} = 0.3.$$

Table 2. Parameters of the asymmetric half-bridge DC/DC converter^[1].

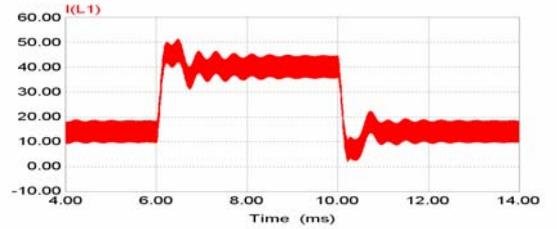
Parameters	Value	Unit
Input Voltage, V_i	400	V
Input Capacitor, C_i	10	μ F
Parasitic Resistance for C_i, R_i	0.1	Ω
Magnetizing Inductance, L_m	∞	μ H
Output Inductance, L_l	40	μ H
Parasitic Resistance for L_l, R_{Ll}	0.15	Ω
Output Capacitance, C_o	1000	μ F
Parasitic Resistance for C_o, R_{Co}	0.01	Ω
Output 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

The parameters of the fuzzy membership functions in Fig. 3 and Fig. 4 are $[e_1, e_2, e_3, e_4, e_5, e_6, e_7] = [-11.4, -5.0, -2.15, 0.0, 2.5, 4.6, 7.6]$ and $[ce^-, 0, ce^+] = [-0.2499, 0.0, 0.2499]$. The output of the fuzzy rule base in Fig. 5 are [NVB, NB, NM, NS, ZE, PS, PM, PB, PVB] = [0.1, 0.2, 0.25, 0.275, 0.3, 0.325, 0.35, 0.4, 0.45]. K_i for the linear integrator in Fig. 2 is 0.002.

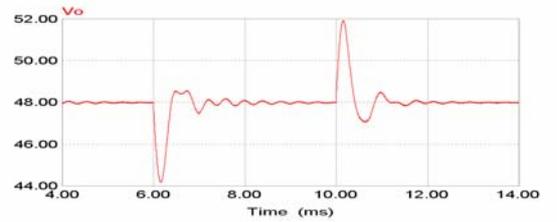
Simulation results carried out with PSIM^[12] for the designed fuzzy controller are shown in Fig. 6 (a), (b), (c) and (d). Here, the load resistance changed from 2.4 [Ω] to 0.8 [Ω] at 6ms and back to 2.4 [Ω] at 10ms. Fig.6 (c) and (d) have the same load changes as Fig. 6 (a) and (b) except 20% parameter error of inductor L_l . From the figure, one can see that the fuzzy controller regulates the output voltage V_o at 48[V] smoothly in 2[ms] as the inductor current i_{Ll} changes to the values required by the load.



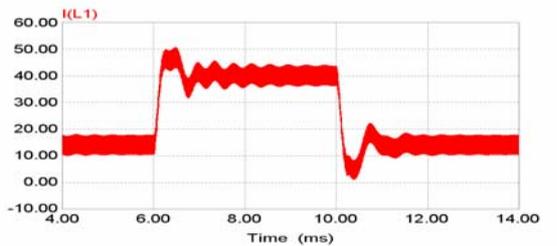
(a)



(b)



(c)



(d)

Fig.6 Output voltages of the current-doubler-rectified asymmetric half-bridge DC/DC converter with the PID Fuzzy controller considered in this paper. (a) V_o , (b) I_{Ll} , (c) V_o , (d) I_{Ll} : (c) and (d) are for the case of 20% parameter error of inductor L_l .

For the purpose of the comparison, simulation results of the type 2 error amplifier^[12] designed with $R_1=4[\text{k}\Omega]$, $R_2=10[\text{k}\Omega]$, $C_1=50[\text{nF}]$ and $C_2=100[\text{pF}]$ via the conventional loop-gain method applied to (8) in Section 2 are shown in Fig. 7 (a), (b), (c) and (d). As it can be seen, the output voltage variation of the PID fuzzy controller is smaller in magnitude and shorter in progress than that of the conventional feedback controller.

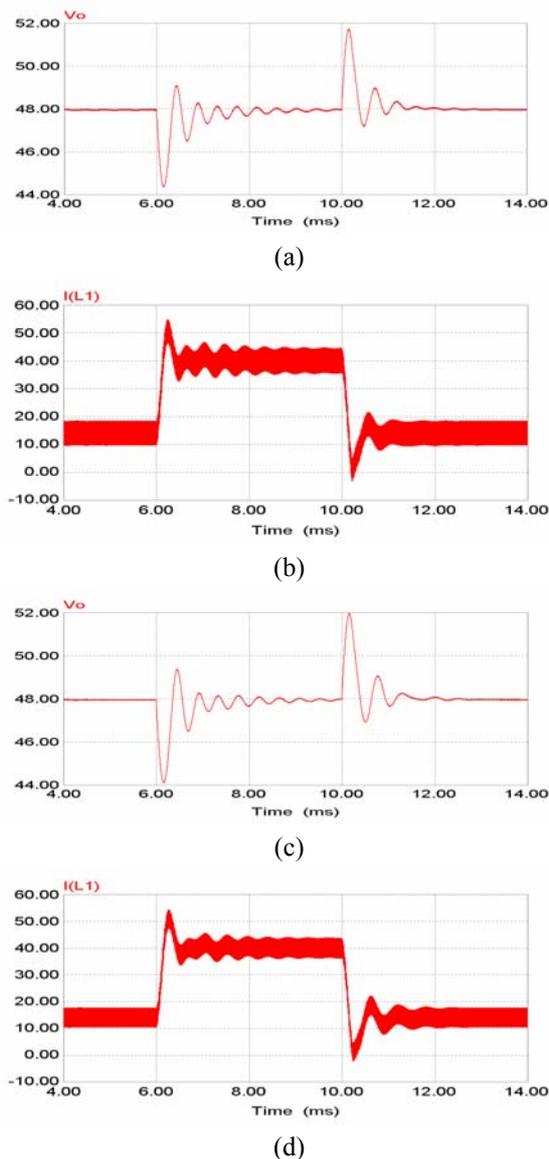


Fig.7. Output voltages of the current-doubler rectified asymmetric half-bridge DC/DC converter with the type-2 controller designed with the conventional design method. (a) V_o , (b) I_{L1} , (c) V_o , (d) I_{L1} : (c) and (d) are for the case of 20% parameter error of inductor L_1

5. Conclusions

In this paper, the PID fuzzy controller was applied to the regulation of the output voltage of the CDRAHB DC/DC converter.

In section 2, the steady-state and dynamic characteristics of the CDRAHB DC/DC converter with state-space averaging method are modeled, which are absolutely necessary when the output voltage controller is designed with the conventional loop gain method.

In section 3, the PID fuzzy control approach is explained to regulate the output voltage of the CDRAHB DC/DC converter. The PID fuzzy controller is simply designed with the 21 IF...THEN statements to reduce the output voltage error.

In section 4, simulations in the time-domain utilizing PSIM program were presented that the performance of the designed PID fuzzy controller is satisfactory when it is compared to that of the conventional feedback controller.

Further investigations yet to be done include the experimental verification.

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