A Novel FPSM Controller for DC-DC Switching Converters

Yong Feng, Shun-Ping Wang, Ping Luo, Quan-Ming Niu, and Zhao-Ji Li

Abstract—This paper presents a novel fuzzy pulse skip modulation (FPSM) controller for switching direct current to direct current (DC-DC) converters based on fuzzy ratiocination modeling approach. Owing to the optimal consideration during the design and the nonlinear characteristics of the controller, improved dynamic responses of the FPSM controller can be achieved over conventional controllers. Compared with conventional proportion integral derivative (PID) control, FPSM control has 60% lower overshoot and 10% lower setting time under the same input voltage and output load change. The presented approach is general and can be applied to other types of DC-DC converters.

Index Terms—Direct current to direct current, fuzzy pulse skip modulation, fuzzy ratiocination modeling approach, pulse skip modulation (PSM).

1. Introduction

It is well known that switching direct current to direct current (DC-DC) power converters are highly nonlinear systems with uncertain parameters owing to the uncertain input voltage and output load during operations. Consequently, the control of DC-DC switching power converters is a difficult task. In this paper, the problem is tackled from the nonlinear control point of view. Pulse skip modulation (PSM) which bases on constant width constant frequency (CWCF) control pulse differs from the aforementioned two.

Without losing universality, a buck DC-DC converter shown in Fig. 1 (a) is used to introduce the principle and characteristics of PSM. Fig. 1 (b) gives the clock pulse and the control signals for three modes of PSM, PWM and PFM. $V_s$ and $V_o$ are the input and output voltage, respectively. Suppose the setting value of output voltage is $V_{ref}$ to the PSM control mode, if the actual output voltage $V_o$ is lower than $V_{ref}$, the CFCW control signals will act on the power device T, and make it operate on the normal on-off state. Otherwise, some control pulses would be skipped in order to keep an off state during the whole cycles to decrease the output voltage and hold its value steady.

From [1] and [3]-[4], we can know that PSM has higher efficiency, quicker response speed and stronger robust characteristics compared with conventional controller, but also has larger overshoot and output ripple. So a fuzzy PSM (FPSM) model was proposed in [3]. It’s shown that FPSM has better transient responses and interference rejection compared to conventional PID-controller. However,
Reference [3] did not set up the mathematic model of FPSM. This paper will solve this problem.

Fig. 1. The topology and control signal of buck converter: (a) topology of buck converter, (b) control signals for different modulation modes.

3. Fuzzy Ratiocination Modeling Approach

Up to now, there are mainly three approaches used to model fuzzy control. The first is derivation approach from given nonlinear system equations. The second is system identification approach using input-output data proposed in [5]. The third one is fuzzy ratiocination modeling approach firstly proposed in [2].

The principle of fuzzy ratiocination modeling approach is as follows: acting the fuzzy ratiocination on the control target, then change the fuzzy knowledge rules base into certain variable coefficient nonlinear different equations using the fuzzy logic system interpolation mechanism, so-called HX equations. Then we can get the mathematic model of the control system. From [3], the system model derived from the novel approach has high consistency with the real model or ideal model.

For simplicity and without losing the universality, a fuzzy controller with two inputs $x_1$ and $x_2$ and a single output $y$ is considered. Assume that

- $x_1 \in [a_i, b_i]$, $x_2 \in [a_j, b_j]$, $y \in [a, b]$
- $A = \{A_i\}$, $1 \leq i \leq p$
- $B = \{B_j\}$, $1 \leq j \leq q$
- $C = \{C_{ij}\}$, $1 \leq i \leq p$, $1 \leq j \leq q$

as the fuzzy sets of the three variables. $x_i, x_j$, and $y$ are the peak value point of $A_i, B_j$ and $C_{ij}$, respectively. Regarding $A$, $B$, and $C$ as linguistic variables, the fuzzy model rules are described as follows.

If $x_1$ is $A_i$ and $x_2$ is $B_j$, then $y$ is $C_{ij}$, $i = 1, 2, \cdots, p$, $j = 1, 2, \cdots, q$.

From the conclusion in [6], the fuzzy logic system can be expressed by a two dimension chip interpolation function.

$$y = F(x_1, x_2) \approx \sum_{i=1}^{p} \sum_{j=1}^{q} A_i(y)B_j(y)y_{ij}.$$  \hspace{1cm} (3)

Assume $A_i$, $B_j$, and $C_{ij}$ have triangular membership function as follows.

$$A_i(y) = \begin{cases} \frac{(y-y_{i1})}{(y_{i1}-y_{i2})}, & y_{i1} \leq y \leq y_{i2} \\ \frac{(y-y_{i2})}{(y_{i2}-y_{i1})}, & y_{i2} \leq y \leq y_{i1} \\ 0, & \text{otherwise.} \end{cases} \hspace{1cm} (4)$$

When $i = 1, 2, \cdots, p$ and $y_{p+1} = y_{i+1}$. In (3), the interpolation function only has relation with the peak value of $C_{ij}$, the shape of membership function need not be considered.

The fuzzy system based on (3) can be expressed as a two order variable coefficient nonlinear differential equation.

$$y = F(x_1, x_2) \approx a(x_1, x_2)x_1 + b(x_1, x_2)x_2 + c(x_1, x_2)x_1x_2 + d(x_1, x_2).$$  \hspace{1cm} (5)

When

$$a(x_1, x_2) = \sum_{i=1}^{p-1} \sum_{j=1}^{q-1} a^{(i,j)}, \quad b(x_1, x_2) = \sum_{i=1}^{p-1} \sum_{j=1}^{q-1} b^{(i,j)}$$

$$c(x_1, x_2) = \sum_{i=1}^{p-1} \sum_{j=1}^{q-1} c^{(i,j)}, \quad d(x_1, x_2) = \sum_{i=1}^{p-1} \sum_{j=1}^{q-1} d^{(i,j)}.$$

If

$$(x_1, x_2) \not\in [x_{i1}, x_{(i+1)}] \times [x_{j1}, x_{(j+1)}],$$

where the rectangle represents a chip$(i, j)$, then

$$a^{(i,j)} = b^{(i,j)} = c^{(i,j)} = d^{(i,j)} = 0.$$  \hspace{1cm} (6)

If

$$(x_1, x_2) \in [x_{i1}, x_{(i+1)}] \times [x_{j1}, x_{(j+1)}],$$

then

$$a^{(i,j)} \approx \frac{x_{2j}(y_{(i+1)}-y_{ij})+x_i(y_{ij+1})-y_{i2}}{(x_{i1}-x_{(i+1)})(x_{2j}-x_{2(j+1)})},$$

$$b^{(i,j)} \approx \frac{x_{1j}(y_{ij+1}-y_{ij})+x_{i+1}(y_{(i+1)j})-y_{i1}}{(x_{i1}-x_{(i+1)})(x_{1j}-x_{1(j+1)})},$$

$$c^{(i,j)} \approx \frac{y_{ij+1}-y_{ij}}{(x_{i1}-x_{(i+1)})(x_{2j}-x_{2(j+1)})},$$

$$d^{(i,j)} \approx \frac{x_{2j}x_{i+1}y_{ij}+x_{i}x_{i+1}y_{ij+1}-x_{2j}x_{i+1}y_{ij+1}}{(x_{i1}-x_{(i+1)})(x_{2j}-x_{2(j+1)})}. \hspace{1cm} (7)$$

Then (5) can be rewritten as undermentioned chip equation.

$$y = a^{(i,j)}x_1 + b^{(i,j)}x_2 + c^{(i,j)}x_1x_2 + d^{(i,j)}.$$  \hspace{1cm} (8)

It should be noticed that $a(x_1, x_2), b(x_1, x_2), c(x_1, x_2)$, and $d(x_1, x_2)$ in (5) depend on the input vector $(x_1, x_2)$. The fuzzy system can be modeled using (10).

4. Design of FPSM Controller

A FPSM circuit is designed to testify the mathematic model and display the characteristics of FPSM converter.
The inputs to the FPSM controller are the output voltage error $e$ and the output voltage error derivative $\Delta e$. The error derivative is proportional to the output voltage derivative $dV_o/dt$, where the derivative of $V_o$ is approximately proportional to the inductor current $I_L$, due to $V_o=V_c$ and $I_o$ is approximately constant over a conduction cycle.

The output is the duty cycle $D$. The controller is designed based on the theory described in Section 3. The system structure is shown in Fig. 2.

![Fig. 2. The system frame of FPSM.](image)

Define the subsets and the membership of fuzzy controller as following:

- $e = \{\text{NB, NM, NS, ZO, PS, PM, PB}\}$
- $\Delta e = \{\text{NB, NM, NS, ZO, PS, PM, PB}\}$
- $D = \{\text{NB, NM, NS, ZO, PS, PM, PB}\}$.

![Fig. 3. The membership function of FPSM.](image)

For each fuzzy input, 7 evenly distributed triangular membership functions are chosen, resulting in 49 rules. The knowledge base is as follows:

<table>
<thead>
<tr>
<th>$e$</th>
<th>$\Delta e$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>NM</td>
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<td>PM</td>
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<td>NS</td>
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<td>PB</td>
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This knowledge base does not necessarily need to exhibit high accuracy; however, it needs to exhibit the right output control directionality. From Fig. 4, it shows that the output of fuzzy controller AND (AND means logical operation) the PSM signal derives the FPSM signal with variable duty cycle. Comparison with the pure PSM control, FPSM still keeps the characteristics that skip more cycles at lighter load. Thanks to the attendance of Fuzzy control, the $D_{\text{max}}$ changes adaptive to the change of load and reduce the skipping cycles at the same load, which can obviously improve the output voltage ripple.

5. Simulation Results and Discussion

After obtaining the fuzzy ratiocination fuzzy model of the buck converter, we can design a fuzzy controller for the converter based on this fuzzy model with small ripple and good dynamic behavior in a wide load range.

The simulation condition is $V_s=10\text{ V}$, $L=50\mu\text{H}$, $C=100\mu\text{F}$, $f_s=100\text{ kHz}$, $V_o=5\text{ V}$. Define the peak point of $e$, $\Delta e$, $D$ as follows:

- $e = \begin{bmatrix} 5 & -1.4 & -0.6 & -0.1 & 0.1 & 0.6 & 1.4 & 5 \end{bmatrix}$
- $\Delta e = \begin{bmatrix} -5 & -2.24 & -0.96 & -0.2 & 0.2 & 0.96 & 2.24 & 5 \end{bmatrix}$
- $D = \begin{bmatrix} 0.65 & 0.60 & 0.60 & 0.50 & 0.50 & 0.50 & 0.42 & 0.35 \\ 0.60 & 0.60 & 0.50 & 0.50 & 0.50 & 0.42 & 0.42 & 0.35 \frac{35}{35} \\ 0.60 & 0.50 & 0.50 & 0.42 & 0.42 & 0.42 & 0.35 & 0.25 \\ 0.50 & 0.50 & 0.50 & 0.42 & 0.42 & 0.42 & 0.25 & 0.25 \frac{15}{15} \\ 0.50 & 0.42 & 0.42 & 0.42 & 0.35 & 0.25 & 0.25 & 0.15 \frac{15}{15} \\ 0.50 & 0.42 & 0.42 & 0.35 & 0.25 & 0.25 & 0.15 & 0.15 \frac{10}{10} \end{bmatrix}$

Inserting (6) to (9), the coefficient of the chip nonlinear equation can be obtained in (11) to (14).

From the four coefficient matrixes, 49 chip nonlinear equations are gained, which are the control arithmetic of the FPSM controller.

It is shown in Fig. 4 that the lighter the load is or the larger the input is, the more cycle number is skipped. Besides the PSM regulating rule, we can see the fuzzy control also affects the system. The duty of control pulse becomes a little...
small. When the load turns light, it results in smaller output ripple.

Fig. 5 shows the simulated transient responses of the FPSM controlled and PID controlled buck converter subject to significant changes of load resistance respectively. Fig. 6 shows the corresponding transient responses of the FPSM controlled and PID controlled buck converter subject to significant changes of input voltage, respectively.

\[
a = \begin{bmatrix}
0.0113 & -0.0486 & 0.0073 & -0.0111 & -0.0222 & -0.0243 & -0.0352 \\
-0.2264 & 0.0937 & -0.1263 & -0.0500 & 0 & 0 & 0.1014 \\
0.1623 & 0 & 0 & 0 & 0.0368 & -0.2450 & 0 \\
0 & -0.7000 & 0.1053 & -0.1750 & -0.4421 & 0.3750 & -0.5000 \\
-0.2899 & 0.1200 & 0 & 0 & 0.0526 & -0.3500 & 0 \\
0 & 0 & -0.1105 & -0.1063 & -0.1579 & 0.0938 & -0.2264 \\
0.0180 & -0.0340 & -0.0300 & -0.0139 & 0.0073 & -0.0486 & 0.0113 \\
\end{bmatrix}
\]

(11)

\[
b = \begin{bmatrix}
0.0070 & -0.1085 & -0.0512 & 0.2778 & 0 & -0.0516 & 0.0099 \\
-0.0634 & 0.0586 & -0.1842 & 0.1500 & 0 & -0.0547 & -0.0634 \\
0.0072 & 0 & -0.1053 & 0 & -0.1105 & 0.0109 & 0.0362 \\
0 & -0.0313 & -0.0526 & -0.0875 & 0.0461 & -0.0391 & -0.0362 \\
0.0058 & -0.0750 & 0 & -0.1750 & 0.0263 & -0.0937 & 0.0362 \\
-0.0290 & 0 & -0.0691 & -0.1188 & -0.2303 & 0.0586 & 0.0634 \\
-0.0403 & 0.0213 & -0.0768 & -0.3472 & 0.0512 & -0.1085 & 0.0070 \\
\end{bmatrix}
\]

(12)

\[
c = \begin{bmatrix}
0.0050 & -0.0217 & -0.0365 & -0.0556 & 0 & 0.0022 & 0.0070 \\
-0.0453 & 0.0977 & -0.1316 & 0.2500 & 0 & 0 & -0.0453 \\
0.0725 & 0 & 0 & 0 & -0.1842 & 0.1094 & 0 \\
0 & -0.3125 & 0.5263 & -0.8750 & 0.4605 & -0.3906 & 0 \\
-0.0580 & 0.1250 & 0 & 0 & -0.2632 & 0.1562 & 0 \\
0 & 0 & -0.1151 & -0.0937 & 0.1645 & -0.0977 & 0.0453 \\
0.0081 & -0.0152 & -0.0110 & 0.0694 & -0.0365 & 0.0217 & -0.0050 \\
\end{bmatrix}
\]

(13)

\[
d = \begin{bmatrix}
0.6158 & 0.3569 & 0.5102 & 0.4444 & 0.3889 & 0.4385 & 0.3007 \\
0.2830 & 0.5563 & 0.3232 & 0.3900 & 0.4200 & 0.4725 & 0.4920 \\
0.5162 & 0.5000 & 0.3989 & 0.4200 & 0.4421 & 0.3255 & 0.4312 \\
0.5000 & 0.4300 & 0.4095 & 0.4025 & 0.3942 & 0.3875 & 0.3812 \\
0.5290 & 0.3480 & 0.4200 & 0.3850 & 0.3447 & 0.4600 & 0.3312 \\
0.3551 & 0.4200 & 0.4863 & 0.4487 & 0.4711 & 0.1938 & 0.4670 \\
0.3298 & 0.4676 & 0.3735 & 0.3194 & 0.2398 & 0.3931 & 0.1342 \\
\end{bmatrix}
\]

(14)

Fig. 4. The output voltage and the gate signal.
overshoot and 10% lower setting time under the same input voltage and output load change. FPSM controller not only offers the DC-DC converter high efficiency, quick response speed, and strong robust characteristics, but also decreases the overshoot and the ripple of the output voltage. The fuzzy model proposed in this paper is general for all topology of DC-DC converters, as well as quasi-resonant DC-DC switching converters. The designs of the fuzzy controllers for them are more or less the same.

Fig. 5. Output voltage response of FPSM controlled and PID controlled buck converter subject to a load pulse changing from 20Ω-5Ω-20Ω when \( V_{in} = 10V \).

Fig. 6. Output voltage response of FPSM controlled and PID controlled buck converter subject to an input voltage pulse changing from 10V-5V-10V when \( R_\text{L} = 20\Omega \).

When start up, the FPSM control has almost no overshoot and has much lower setting time and lower overshoot under the same input voltage and output load change. The results show that the responses of the FPSM controlled buck converter are much better than those of the PID controlled buck converter in terms of response time and overshoot. It also shows the FPSM controller based on fuzzy ratiocination modeling approach is feasible and has better dynamic performance than conventional PID-controller.

6. Conclusions

The fuzzy ratiocination modeling approach for nonlinear system is firstly applied to DC-DC power converters based on PSM mode in this paper. Based on this fuzzy plant model, a nonlinear fuzzy controller has been designed with small output voltage ripple and good dynamic behavior for a PSM converter. When the regulated converter is subject to significant changes of load resistance and input voltage, the fuzzy controller can offer much better transient responses than a conventional PID controller. Compared to conventional PID control, FPSM control has 60% lower overshoot and 10% lower setting time under the same input voltage and output load change. FPSM controller not only offers the DC-DC converter high efficiency, quick response speed, and strong robust characteristics, but also decreases the overshoot and the ripple of the output voltage. The fuzzy model proposed in this paper is general for all topology of DC-DC converters, as well as quasi-resonant DC-DC switching converters. The designs of the fuzzy controllers for them are more or less the same.

References


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