A DC-DC converter anti-interference system based on T-S fuzzy sliding mode control

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Abstract. With the wide application of switching power supply, the research on its control method has become a hot spot at present, and DC-DC converter is one of the switching power supplies with the highest frequency. However, in daily use, the input voltage of the converter may fluctuate greatly, so it is very important to obtain a stable DC output voltage. Therefore, this paper proposes a nonlinear composite control strategy method based on T-S fuzzy sliding mode control for the system disturbance problem of DC-DC converter. After establishing the T-S fuzzy model, the variable structure control theory is added, and the sliding mode surface and sliding mode control law are designed and their stability is proved by Lyapunov function. The simulation results show that the proposed control method has a good control effect and can keep the system robust.

1. Introduction
In electronic power technology, DC-DC (Direct Current-Direct Current) converter is widely used as a switching power supply circuit topology. DC-DC converters include Buck type, Boost type and Buck-Boost type. In essence, DC-DC converter is a strongly nonlinear system, and fuzzy sliding mode control can effectively control complex nonlinear systems in uncertain environment. It does not rely on accurate mathematical models, and has good robustness to the problem of unstable system parameters in DC-DC converter[1-4]. Literature [5] designed a second-order sliding mode controller based on Buck converter. The feedback quantity is the output voltage, however, the system state quantity is single, resulting in low robustness. Reference [6] proposes to adopt PI regulation. Because the parameters of the actual system are uncertain, it is difficult to calculate the precise parameters. Therefore, the voltage and current double-loop control strategy is adopted. Literature [7] studies the fuzzy PI controller with double loops of voltage and current for interleaved DC-DC converters, but it cannot respond sensitively to large signal disturbance items in the system. To solve the above problems, this paper proposes an anti-interference system of DC-DC converter based on T-S fuzzy sliding mode control, which can solve the problems of voltage and current instability in DC-DC system.
2. Design of Fuzzy Controller of Buck DC-DC Converter

2.1. Average state model of Buck DC-DC converter

This paper takes Buck DC-DC converter as an example, and the schematic diagram of Buck converter is shown below.

![Buck converter schematic](image)

The working process of buck converter is divided into two stages: the first stage is the charging stage of inductor, and the second stage is the discharging stage of inductor. At this time, if the difference between the reference voltage and the output voltage is \( x_1 \), the change rate of voltage difference is \( x_2 \), and the inductance current is \( x_3 \), the mathematical model of the three state variables is formula (1)[8]

\[
\begin{align*}
  x_1 &= V_{\text{ref}} - V_1 \\
  x_2 &= \frac{1}{C} \int i_L dt + d_1 \\
  x_3 &= i_L + d_2
\end{align*}
\]

(1)

where reference voltage \( V_{\text{ref}} \), output voltage \( V_1 \), input voltage \( V_g \) and inductor current \( i_L \); \( i_L = \int \frac{uV_g - V_1}{L} dt \), \( d_1 \), \( d_2 \) is the interference of the system. The average state model of DC-DC converter under CCM operation is established as follows[9]

\[
\begin{align*}
  \dot{x}(t) &= Ax(t) + Bu(t) + B_u \delta(t) \\
  y(t) &= Cx(t)
\end{align*}
\]

(2)

where \( x(t) = [x_1 \ x_2 \ x_3]^T, u(t) = \frac{V_g}{V_1}, \delta(t) = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \); \( A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{1}{RC} & 0 \\ 0 & 0 & 0 \end{bmatrix}, \ B = \begin{bmatrix} 0 & 0 \\ -\frac{1}{LC} & \frac{1}{LC} \end{bmatrix}, B_u = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, C = [1 \ 0 \ 0] \). Among them, \( A, B, C, B_u \) are known real constant matrices, \( x(t) \) is state variables \( u(t) \), input variables, output variables \( y(t) \) and interference items \( \delta(t) \).
2.2. T-S fuzzy control model of DC-DC converter

T-S fuzzy controller is established based on T-S fuzzy rules, and the average state model of DC-DC converter is transformed into T-S fuzzy model. The fuzzy rules are as follows

\[
\text{IF } \theta_1(t) \text{ is } M_{11}, \theta_2(t) \text{ is } M_{12}, \ldots, \theta_p(t) \text{ is } M_{ip},
\]

\[
\text{THEN } \dot{x}(t) = Ax(t) + Bu(t) + B_\delta(t) \quad y(t) = Cx(t)
\]

where \( \theta_1(t), \theta_2(t), \ldots, \theta_p(t) \) is prerequisite variable. \( M_{11}, M_{12}, \ldots, M_{ip} \) is fuzzy set. The fuzzy model of the system can be obtained

\[
\dot{x}(t) = \sum_{i=1}^{n} h_i(\theta(t)) \left[ (A_i + \Delta A_i) x(t) + Bu(t) + B_\delta(t) \right]
\]

\[
y(t) = Cx(t)
\]

where \( h_i(\theta(t)) = \frac{\mu_i(\theta(t))}{\sum_{i=1}^{n} \mu_i(\theta(t))} \), for all moments, \( \sum_{i=1}^{n} \mu_i(\theta(t)) > 0 \), therefore \( h_i(\theta(t)) \geq 0 \),

\[
\sum_{i=1}^{n} h_i(\theta(t)) = 1; \quad A_i, i = 1, 2, 3, 4, \Delta A_i = E_i \Delta F_i H_j, \quad \text{among } \Delta F_i \text{ is an uncertain matrix function satisfying Lebesgue measurability}, n \text{ is a fuzzy rule number.}
\]

2.3. Global fuzzy control model of DC-DC converter

The T-S fuzzy model is transformed and decomposed into variables, and a global fuzzy model is established. Firstly, the rank of the matrix is 2, and singular value decomposition can be performed as follows

According to the mathematical theorem in matrix theory, we can know

\[
B = UDV^H, U = [U_1 U_2], V = B^T U_1 \Delta^{-1}
\]

where

\[
\Delta = \begin{bmatrix}
\frac{2}{EC^2} & 0 \\
0 & \frac{2}{E}
\end{bmatrix}, U_1 = \begin{bmatrix}
0 & 0 \\
1 & 0
\end{bmatrix}, U_2 = \begin{bmatrix}
1 & 0 \\
0 & 0
\end{bmatrix}, V = \begin{bmatrix}
\frac{LC}{2} & L \\
\frac{LC}{2} & \frac{L}{2}
\end{bmatrix}, D = \begin{bmatrix}
\frac{2}{EC^2} & 0 \\
0 & \frac{2}{E}
\end{bmatrix}
\]

After finishing, you can get

\[
B = \begin{bmatrix}
0 & 0 & 1 \\
1 & 0 & 0 \\
0 & 1 & 0
\end{bmatrix}, \Delta = \begin{bmatrix}
\frac{LC}{2} & L \\
\frac{LC}{2} & \frac{L}{2}
\end{bmatrix}
\]

After state transformation, Let \( T = [U_1 U_2]^T, z(t) = Tx(t) \), the transformed global fuzzy model can be obtained

\[
\dot{z}(t) = \sum_{i=1}^{n} h_i(\theta(t)) \left[ (TA_iT^{-1} + T \Delta A_i T^{-1}) z(t) + [0_{1 \times 2} \Delta V]^H \right] u(t) + TB_\delta(t)
\]

Assume that

\[
A(t) = \sum_{i=1}^{n} h_i(\theta(t)) \left( TA_iT^{-1} + T \Delta A_i T^{-1} \right)
\]
The transformed global fuzzy model can be obtained as follows
\[
\dot{z}(t) = A(t)z(t) + B(t)u(t) + C(t)\delta(t)
\]

3. Design of sliding mode controller for Buck DC-DC converter

3.1. Select the appropriate sliding surface

Based on the global fuzzy model, the sliding mode switching function is selected as
\[
s(t) = Gz(t)
\]
\[
\dot{s}(t) = G\dot{z}(t)
\]
where \( G \) is a parameter matrix and \( G = [k_1, k_2, 1] \) is in sliding mode control, the parameters \( k_1, k_2, 1 \) should satisfy Hurwitz polynomial, that is \( k_1 + k_2 p + p^2 = 0 \), the real part of eigenvalue is negative; In this paper, the \( k_1 = 4, k_2 = 4 \) empirical calculation satisfies the conditions.

3.2. Verify the stability of the system

The stability of sliding mode motion of sliding mode control system depends on the design of sliding mode, so it is necessary to ensure the stability of sliding mode equation. The stability is verified by constructing Lyapunov function.

Lyapunov function \( V = \frac{1}{2} s(t)^2 \) can be obtained by derivation \( \dot{V} = s(t)\dot{s}(t) \). In order to ensure the dynamics of sliding mode, the following conditions need to be met
\[
\dot{V} = s(t)\dot{s}(t) < 0
\]
To ensure \( \dot{V} = s(t)\dot{s}(t) < 0 \), the sliding mode control law is designed as follows
\[
u(t) = G\sum_{i=1}^{n} h_i(\theta(t))\eta \text{sgn}(s) - \left[ (V^{ii})^{-1} \Delta^{-1} (TAT^{-1} + T\Delta AT^{-1}) z(t) + (V^{ii})^{-1} \Delta^{-1} TB_{w} \delta(t) \right]
\]
It can be deduced that
\[
\dot{V} = s(t)\dot{s}(t)
\]
\[
= GG^{ii}s(t) \left[ A(t)z(t) + B(t)u(t) + C(t)\delta(t) \right]
\]
\[
= GG^{ii}s(t) \left[ \sum_{i=1}^{n} h_i(\theta(t)) \left( TAT^{-1} + T\Delta AT^{-1} \right) z(t) + B(t)u(t) + \sum_{i=1}^{n} h_i(\theta(t))TB_{w} \delta(t) \right]
\]
\[
= -GG^{ii}\eta \text{sgn}(s(t))
\]
\[
= -GG^{ii}\eta |s(t)| < 0
\]
where \( \eta > 0 \) is verified by Lyapunov function, which proves that the system has good robustness.

4. Simulation analysis

In order to verify the effectiveness of the controller, a Matlab simulation model is established and verified in this paper. The simulation parameters of Buck converter are shown in Table 1. Figure 2-4
shows the simulation results of three state variables under sliding mode control, and Figure 5 shows the stability analysis results of sliding mode surface.

Table 1. Simulation parameters

| parameter                        | value |
|----------------------------------|-------|
| Input voltage $V_g / V$          | 24    |
| Reference voltage $V_{ref} / V$  | 12    |
| Inductance $L / mH$              | 10    |
| Filter capacitor $C / \mu F$     | 750   |
| Load $R_L / \Omega$              | 24    |
| Sliding mode surface coefficient $k_1, k_2, 1$ | 4,4,1 |

Fig 2. Dynamic response of difference between input voltage and output voltage under sliding mode control

Fig 3. Dynamic response of inductor current under sliding mode control

Fig 4. Dynamic response of the rate of change of voltage difference under sliding mode control

Fig 5. Stability analysis of sliding mode surface

5. Summarize
In this paper, the irregular disturbance in the system is considered for DC-DC converter, and the T-S fuzzy model is established, on this basis, the sliding mode control is added, and the combination of the two can better solve the system disturbance problem and get the results. The simulation results show that: 1) under the control of fuzzy sliding mode, the control variable can quickly reach a stable state; 2) After adding disturbance term into the mathematical model, it has no great influence on the simulation results, so it can be concluded that the anti-interference effect of the system is obvious; 3) The designed controller can effectively improve the static and dynamic characteristics and robustness of the system.

Acknowledgement
This work was supported by Key R&D Program of Liaoning Province (2020JH2/10300101), Liaoning Revitalization Talents Program (XLYC1907138), Natural Science Foundation of Liaoning Province
(2019-MS-239), Technology Innovation Talent Fund of Shenyang (RC200252) and Key R&D Program of Shenyang (GG200252).

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