Adaptive Non-singular Terminal Sliding Mode Control for DC-DC Converters

Liping FAN, Yazhou YU
College of Information, Shenyang University of Chemical Technology, Shenyang, 110142, China
fanliping@syuct.edu.cn

***Abstract*—DC-DC converters have some inherent characteristics such as high nonlinearity and time-variation, which often result in some difficulties in designing control schemes. An adaptive non-singular terminal sliding mode control method is presented in this paper. Non-singular terminal sliding mode control is used to make the converter reach steady state within a limited time, and an adaptive law is integrated to the non-singular terminal sliding mode control scheme to make the proposed control method have adaptive ability to disturbances, and overcome the limitation on non-singular terminal sliding mode control scheme caused by disturbance boundary value. Simulation results show the validity of this adaptive non-singular terminal sliding mode control approach.**

***Index Terms*—non-singular, terminal sliding mode control, adaptive, DC-DC converter**

I. Introduction

DC-DC converters have been widely used in most of the industrial applications such as DC motor drives, computer systems and communication equipments. Design of high performance control is a challenge because of its nonlinear and time variant nature [1]. Generally, linear conventional control applied to DC-DC converter failed to accomplish robustness under nonlinearity, parameter variation, load disturbance and input voltage variation [2]-[4].

The sliding mode controller (SMC) is a kind of nonlinear controller which was introduced for controlling variable structure systems. SMC is one of the effective nonlinear robust control approaches since it provides system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding model [5]. Its major advantages are the guaranteed stability and the robustness against parameter, line, and load uncertainties. Moreover, being a controller that has a high degree of flexibility in its design choices, the SMC is relatively easy to implement as compared with other types of nonlinear controllers. Such properties make it highly suitable for control applications in nonlinear systems [6]. This explains the wide utilization of SMCs in various industrial applications [7]. The strong robustness of SMC plays a very important role in guaranteeing the normal operation of DC converter. SMC can make the DC-DC converter provide stable output even when load varying or the input voltage varies [8].

But in practical systems, because of the delay in time and space, the discontinuous switch control of SMC may cause some "Chattering" problems. Chattering may arouse the unmodelled properties and affect the control performance of the system [9]. On the other hand, because the movement of the sliding mode is asymptotically stable, classical sliding mode control can not guarantee the system state converge to equinoctial point within a finite time.

Terminal sliding mode control has the advantage of finite time convergence and tiny steady state error [10]. But there exist singular points in conventional terminal siding mode control [11]. Nonsingular terminal sliding mode control can avoid the singularity [12], but the upper bounds of the disturbances usually must be known for calculating the switching gain [13].

Adaptive control techniques have also successfully advanced in tackling control problems for uncertain nonlinear systems [14]-[15]. To make the controlled system realize finite time convergence even in the condition of unknown boundary disturbances and overcome the singular problem in designing terminal SMC synchronously, a kind of adaptive estimation method was integrated to nonsingular terminal SMC. To weaken the chattering caused by SMC, the switching item in controller was eliminated.

This paper is organized as follows. The mathematical model for a typical Buck DC-DC converter is described in Section II. Section III presents a brief description of designing a nonsingular terminal sliding mode controller. Designing an adaptive nonsingular terminal sliding mode controller is given in Section IV. In Section V, simulation results are presented to confirm the effectiveness and the applicability of the proposed method.

II. Model of DC-DC Converter

A basic DC-DC converter circuit known as the Buck converter is illustrated in Fig. 1, consisting of one switch, a fast diode and RLC components. The switch can be implemented by one of three-terminal semiconductor switches, such as IGBT or MOSFET.

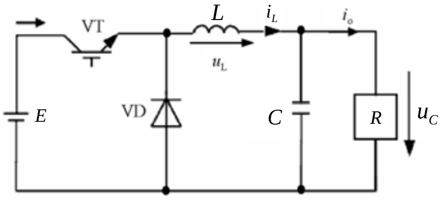

Figure1. Buck DC-DC converter

When the converter work in a Continuous Conduction Mode, the system can be described as [10]

$$\begin{bmatrix} \dot{i}_L \\ \dot{u}_c \end{bmatrix} = \begin{bmatrix} 0 & -\dfrac{1}{L} \\ \dfrac{1}{C} & -\dfrac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ u_c \end{bmatrix} + \begin{bmatrix} \dfrac{E}{L} \\ 0 \end{bmatrix} u \qquad (1)$$

where u is the switching state, when u=1, the switch VT is

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turned on, and when u=0, VT is off.

Select the output voltage and its derivative as system state variables, that is

$$\begin{cases} x_1 = u_c \\ x_2 = \dfrac{\mathrm{d}u_c}{\mathrm{d}t} \end{cases} \tag{2}$$

then the state space model describing the system is derived as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\dfrac{x_1}{LC} - \dfrac{x_2}{RC} + \dfrac{E}{LC}u \end{cases} \tag{3}$$

When the switching frequency is high enough and ripples are small, if we suppose the duty ratio of a switching period is d, then the state space average model can be rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\dfrac{x_1}{LC} - \dfrac{x_2}{RC} + \dfrac{E}{LC}d \end{cases} \tag{4}$$

Consider that disturbances caused by parametric variation may occur in running processes, the model of the converter can be amended as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\dfrac{x_1}{LC} - \dfrac{x_2}{RC} + \dfrac{E}{LC}d + F \end{cases} \tag{5}$$

where F denotes the whole disturbances the system suffered. Other parameters such as L, C, R, E denote the given definite part.

III. DESIGNING OF NONSINGULAR TERMINAL SMC

First a nonsingular terminal SMC for DC-DC converter modeled as equation (5) was designed. It is assumed that F is bounded and $F \le l_g$, $l_g > 0$.

Suppose the expected tracking voltage is r, then the tracking error and its derivative are defined as $e = x_1 - r,\ \dot{e} = x_2 - \dot{r}$.

The sliding surface of this nonsingular terminal SMC is chosen as

$$s = e + \frac{1}{\beta}\dot{e}^{\frac{p}{q}} = (x_1 - r) + \frac{1}{\beta}(x_2 - \dot{r})^{\frac{p}{q}} \tag{6}$$

where $\beta > 0$, p and q are positive odd constants, and $1 < p/q < 2$.

Suppose the time from $s(0) \ne 0$ to $s = 0$ is t_r, and the time from t_r to when the tracking error is zero is t_s. When the system reaches the sliding surface, there exists

$$s = e + \frac{1}{\beta}\dot{e}^{\frac{p}{q}} = 0 \tag{7}$$

By transforming, the following equation can be derived

$$\dot{e} = -\beta^{\frac{q}{p}} e^{\frac{q}{p}} \tag{8}$$

then t_s can be obtained as follows

$$t_s = \frac{p}{\beta^{\frac{q}{p}}(p-q)} \left| e(t_r) \right|^{1-\frac{q}{p}} \tag{9}$$

By adjusting p, q and β, the system can reach steady state in a limited time of t_s.

Define Lyapunov function as

$$V = \frac{1}{2}s^2 \tag{10}$$

then it results

$$\dot{V} = s\left(x_2 - \dot{r} + \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}\left(-\frac{x_1}{LC} - \frac{x_2}{RC} + \frac{E}{LC}d + F - \ddot{r}\right)\right) \tag{11}$$

The nonsingular terminal sliding mode controller is designed as

$$d = -\frac{LC}{E}\left(-\frac{x_1}{LC} - \frac{x_2}{RC} - \ddot{r} + \beta\frac{q}{p}(x_2 - \dot{r})^{2-\frac{p}{q}} + (\eta + l_g)\operatorname{sgn}(s)\right) \tag{12}$$

where $\eta > 0$.

Substituting (12) into (11) leads to

$$\dot{V} = s\dot{s} = \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}\left(sF - (\eta + l_g)|s|\right) \tag{13}$$

because

$$1 < \frac{p}{q} < 2 \tag{14}$$

so

$$0 < \frac{p}{q} - 1 < 1 \tag{15}$$

Because p and q are positive odd constants, when $x_2 - \dot{r} \ne 0$, there exists

$$(x_2 - \dot{r})^{\frac{p}{q}-1} > 0 \tag{16}$$

so

$$\dot{V} \le \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(-\eta|s|) = -\frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}\eta|s| = -\eta'|s| \tag{17}$$

where

$$\eta' = \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}\eta > 0 \tag{18}$$

Therefore the controller can meet the demand of Lyapunov stability.

Merge (12) to (5), then

$$\dot{x}_2 = F + \ddot{r} - \beta\frac{q}{p}(x_2 - \dot{r})^{2-\frac{p}{q}} - (\eta + l_g)\operatorname{sgn}(s) \tag{19}$$

When $x_2 - \dot{r} = 0$, there exist

$$\dot{x}_2 - \ddot{r} = F - (\eta + l_g)\operatorname{sgn}(s) \tag{20}$$

Because $F \le l_g$, so if $s > 0$, then $\dot{x}_2 - \ddot{r} \le -\eta$, while if $s < 0$, then $\dot{x}_2 - \ddot{r} \ge \eta$. The phase trajectory is shown in Fig.2. It can be seen from the trajectory that the controlled system can reach the sliding surface within a finite time.

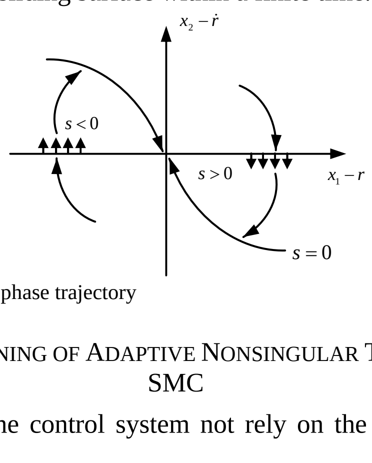


Figure 2. System phase trajectory

IV. DESIGNING OF ADAPTIVE NONSINGULAR TERMINAL SMC

To make the control system not rely on the disturbance boundary values, adaptive estimation to disturbance F is carried out, and then the nonsingular terminal sliding mode controller is amended. The estimated error is defined as

$$\tilde{F} = F - \hat{F} \tag{21}$$

where $\hat{F}$ is the estimation of F.

Lyapunov function is defined as

$$V = \frac{1}{2}s^2 + \frac{1}{2\gamma}\tilde{F}^2 \tag{22}$$

then the following relation can be derived

$$\begin{aligned}\dot{V} &= s(x_2 - \dot{r} + \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(-\frac{x_1}{LC} - \frac{x_2}{RC} \\ &+ \frac{E}{LC}d + \hat{F} - \ddot{r})) - \frac{1}{\gamma}\tilde{F}(\dot{\hat{F}} - \gamma s\frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1})\end{aligned} \tag{23}$$

To eliminate the influence which the estimated error bring onto the system, the estimated controlled variable is selected as

$$\dot{\hat{F}} = \gamma s\frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1} \tag{24}$$

The control input is designed as

$$d = -\frac{LC}{E}(-\frac{x_1}{LC} - \frac{x_2}{RC} + \hat{F} - \ddot{r} + \beta\frac{q}{p}(x_2 - \dot{r})^{2-\frac{p}{q}} + ws^{\frac{m}{n}} + hs) \tag{25}$$

where $w > 0$, $h > 0$, $m < n$, and m, n are positive odd constants. There is no switching item in this control law, and thereby system chattering is eliminated.

Substituting (24) and (25) into (23) leads to

$$\dot{V} = -\frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(ws^{\frac{m+n}{n}} + hs^2) \tag{26}$$

Because equation (14) and (15) are satisfied, and meanwhile p and q are positive odd constants, so when $x_2 - \dot{r} \neq 0$ comes into existence, equation (16) is satisfied.

On the other hand, because $m < n$, and m, n are positive odd constants, so when $s \neq 0$ comes into existence, the following condition is satisfied

$$s^{\frac{m+n}{n}} > 0 \tag{27}$$

With the condition of $x_2 - \dot{r} \neq 0$, we have

$$\dot{V} = -\frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(ws^{\frac{m+n}{n}} + hs^2) \le 0 \tag{28}$$

so Lyapunov stability can be satisfied.

Substituting control input (25) into model (5) leads to

$$\dot{x}_2 = F - \hat{F} - \beta\frac{q}{p}(x_2 - \dot{r})^{2-\frac{p}{q}} - ws^{\frac{m}{n}} - hs + \ddot{r} \tag{29}$$

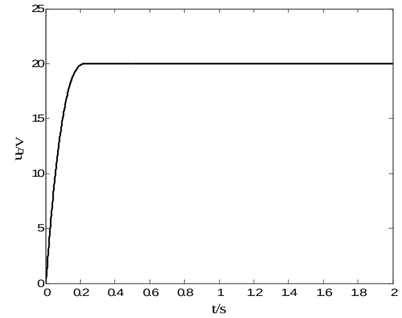
By transforming it can be rewritten as

$$\dot{x}_2 - \ddot{r} = F - \hat{F} - ws^{\frac{m}{n}} - hs \tag{30}$$

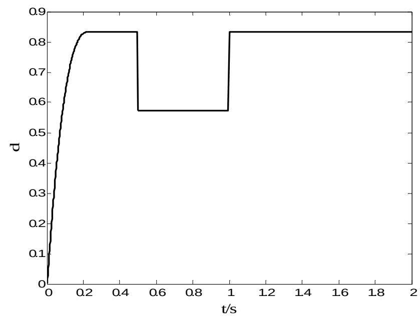
Suppose that $x_2 - \dot{r} = 0$ is satisfied, it can be seen from Fig.2 that if $s > 0$, the control system can reach sliding surface only when $\dot{x}_2 - \ddot{r} < 0$ comes into existence. This requires the condition of $F - \hat{F} < ws^{\frac{m}{n}} + hs$ is satisfied when $s > 0$. In a similar way, $F - \hat{F} > ws^{\frac{m}{n}} + hs$ is satisfied when $s < 0$. By adjusting parameters of the control system, the above mentioned conditions can be satisfied.

V. SIMULATION RESULTS

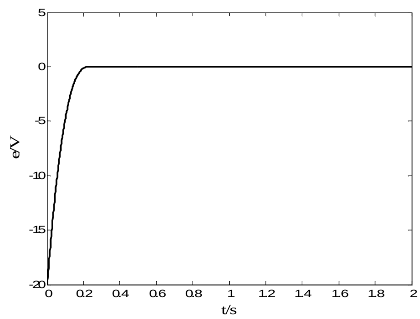
The proposed adaptive nonsingular terminal SMC was used to DC-DC converter and simulation operation was carried out. Parameters of DC-DC converter are chosen as $L = 80\mu\text{H}$, $E = 24\text{V}$, $R = 8\Omega$, $C = 2000\mu\text{F}$. The expected tracking voltage is $r = 20\text{V}$. The initial state of this system is $x = [0 \quad 0]^{\text{T}}$ .The main parameters used in designing controller are $\gamma = 50$, $\beta = 400$, $q = 3$, $p = 5$, $m = 3$, $n = 5$, $w = 5000$, $h = 2000$.



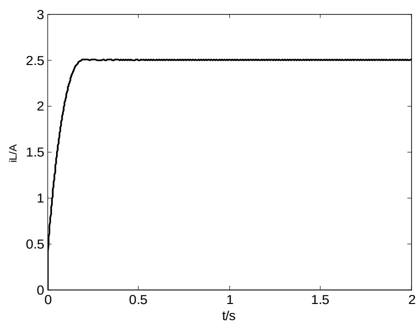
(a) Output voltage waveform



(b) Waveform of duty cycle



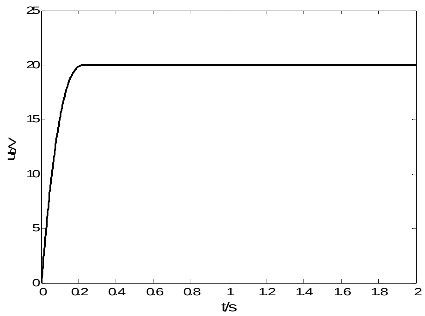
(c) Tracking error waveform



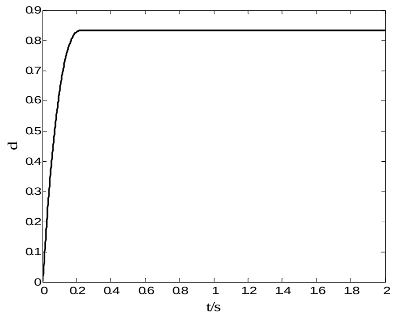
(d) Waveform of inductor current

Figure 3. Simulation results for converter with source fluctuation

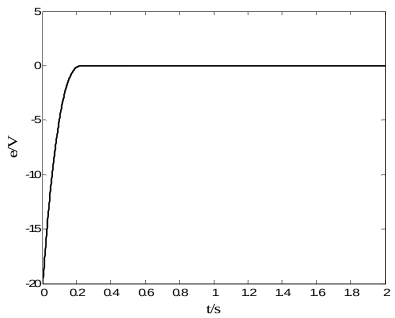
Fig.3 shows the responding profiles of output voltage, control input, tracking error and inductor current corresponding to source variation. The source voltage varies from 24V to 35V at the time of 0.5s and returns to 24V at the time of 1s. It can be seen from these curves that the voltage output can tracking the given voltage with small rise time and the tracking error is almost zero. Because the output voltage is proportional to the product of duty cycle and source voltage, when the source voltage changes, the tracking output voltage keep steady by adjusting duty cycle *d*. Chattering is eliminated from this system.



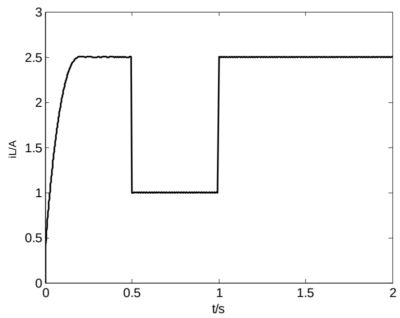
(a) Output voltage waveform



(b) Waveform of duty cycle



(c) Tracking error waveform



(d) Waveform of inductor current

Figure 4. Simulation results for converter with load fluctuation

Fig.4 shows the responding profiles corresponding to load fluctuation. The load resistance varies from 8 Ω to 20 Ω at the time of 0.5s and returns to 8 Ω at the time of 1s. From these curves we can see that the tracking output voltage is with small rise time and nearly zero error, and also there is no chattering.

VI. Conclusions

Nonsingular sliding mode control integrated with adaptive disturbance estimation can overcome the influence which unknown border disturbances bring about to control system, and guarantee DC-DC converter keep good dynamic and steady performances even if it undergo arbitrary random disturbances. The output can follow the given well, and the disturbances almost do not affect the output, and meanwhile, chattering caused by SMC is eliminated in such system.

References

[1] S. G. Kadwane, S. Gupta, B. M. Karan, T Ghose, “Practical Implementation of GA Tuned DC-DC Converter,” ACSE Journal, Vol.6, pp. 89-96, 2006.

[2] A. Sahbani, K. B. Saad, M. Benrejeb, “Chattering Phenomenon Supression of Buck Boost DC-DC Converter with Fuzzy Sliding Modes Control,” International Journal of Electrical and Computer Engineering, Vol. 3, pp. 258-264, 2008.

[3] K. Udhayakumar, P. Lakshmi, K. Boobal, “Hybrid Posicast Controller for a DC-DC Buck Converter,” Serbian Journal of Electrical Engineering, Vol. 5, 121-138, pp. 2008.

[4] V. S. C Racirah, P. C. Sen, “Comparative Study of Proportional-Integral, Sliding Mode, and Fuzzy Logic Controllers for Power Converters,” IEEE Transactions on Industry Applications, Vol. 33, pp. 518-524, 1997.

[5] R. J. Wai, “Adaptive Sliding-mode Control for Induction Servomotor Drive,” IEE Proceedings- Electric Power Applications, Vol. 147, pp. 553-562, 2000.

[6] S. Frikha, M. Djemel, N. Derbel. “Adaptive Neuro Sliding Mode Control for Multivariable Nonlinear System with State Observer,” International Journal of Computational Cognition. Vol. 8, pp. 9-16, 2010.

[7] Y. He, W. Xu, Y. Cheng, “A Novel Scheme for Sliding-Mode Control of DC-DC Converters with a Constant Frequency Based on the Averaging Model,” Journal of Power Electronics, Vol. 10, pp. 1-8, 2010.

[8] J. Tsai and Y. Chen, “Sliding mode control and stability analysis of buck DC-DC converter”, International Journal of Electronic, Vol. 94, pp. 209-222, 2007.

[9] C. S. Chiu, Y. T. Lee, C. W. Yang, “Terminal Sliding Mode Control of DC-DC Buck Converter,” Communications in Computer and Information Science, Vol. 65, pp. 79-86, 2009.

[10] D. Zhao, S. Li, F. Gao, “A New Terminal Sliding Mode Control for Robotic Manipulators,” International Journal of Control, Vol.82, pp. 1804-1813, 2009.

[11] M. Jin, J. Lee, P. H. Chang, C. Choi, “Practical Nonsingular Terminal Sliding-Mode Control of Robot Manipulators for High-Accuracy Tracking Control,” IEEE Transactions on Industrial Electronics, Vol. 56, No. 9, p. 3593-3601, 2009.

[12] Y. Feng, S. Bao, X. Yu, “Inverse Dynamics Nonsingular Terminal Sliding Mode Control of Two-Link Flexible Manipulators,” International Journal of Robotics and Automation, Vol. 19, p. 91–102, 2004.

[13] J. Tsai, Y. Chen, “Sliding Mode Control and Stability Analysis of Buck DC-DC Converter,” International Journal of Electronic, Vol. 94, pp. 209-222, 2007.

[14] O. Barambones, P.Alkorta, A. J. Garrido, I. Garrido, F.J. Maseda, “An Adaptive Sliding Mode Control Scheme for Induction Motor Drives,” International Journal of Circuits, Systems and Signal Processing. Vol. 1, pp. 73-79, 2007.

[15] F. Qiao, Q. Zhu, A. Winfield, C. Melhuish, “Adaptive Sliding Mode Control for MIMI Nonlinear Systems based on a Fuzzy Logic Scheme,” International Journal of Automation and Computing. Vol.1, pp. 51-62. 2004.