Extended Super Twisting Finite-Time Controller Design for DC/DC Buck Converters under Uncertain Conditions

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***Abstract*—To build the controller for Buck type DC/DC converters under uncertainty, a Super Twisting Algorithm (STA) based on homogeneity theory extension is proposed to achieve robust control with finite time stability. The Super Twisting Algorithm is extended to second-order systems, and its finite time stability is demonstrated based on the theory of homogeneity. Finally, simulation experiments and comparisons with homogeneous second-order sliding mode and ordinary sliding mode control methods indicate the superiority of the proposed method in combating uncertainty.**

***Keywords*—buck, sliding mode, homogeneity theory, Super Twisting Algorithm, extended**

I. Introduction

Owning to the fluctuation and intermittency characteristics in the supply of renewable energy, processing of control technology and power electronic conversion technology are indispensable in its development and construction where DC/DC converters play a pivotal role in power electronic conversion. In-depth research on DC/DC converter control strategies is of great significance for the stable operation and the improvement of power efficiency [1].

In the real world, DC/DC converters are influenced by their internal uncertainties and external disturbances. When significant changes occur in loads or parameters, the performance of existing classical control methods may not meet the requirements. The sliding mode control method has incomparable strong points including fast dynamic response and high stability when dealing with uncertainty [2-3]. Reference [4] reconstructed a discrete voltage model with concentrated disturbances, designed a globally robust discrete integral sliding mode voltage controller, and improved the dynamic performance and disturbance resistance of the output voltage. Reference [5] proposed sliding mode controller for bidirectional DC/DC under non ideal conditions, and separately designed sliding mode current and voltage controllers to effectively control the stability of the bidirectional system. Reference [6] constructed a novel fixed time sliding mode surface and sliding mode convergence law which improved the convergence rate when moving away from the system origin and ensured the stability of the system within a fixed time. In reference [7], a second-order sliding mode controller was adopted for the Buck to reduce the use of inductance current sensors and simplified it to only retain the load terminal voltage sensors, which saves the cost of control equipment.

Classical sliding mode control methods have drawbacks of chattering and relative order constraints while the emergence of high-order sliding mode control methods has overcome these drawbacks. Reference [8] proposed a fixed time output voltage regulation algorithm based on variable gain second-order sliding mode control. A sliding mode variable with a relative order of 2 was constructed based on the obtained mathematical model, and a novel gain variable sliding mode control algorithm was proposed to achieve a fixed time output voltage control with convergence time independent of the initial system value. Reference [9] proposed a novel dual Buck full bridge grid connected inverter topology, which uses fewer components and has a simple structure adopting a dual second-order sliding mode control strategy with capacitor voltage and inductor current.

STA is the only continuous and applicable algorithm among existing second-order sliding mode control methods for first-order systems, which can significantly reduce chattering. But what restricts its development is its limitation on the relative order, which can only be used for systems with sliding mode surfaces of relative order 1. How to extend the idea of this method to second-order or even higher-order systems is a worthwhile question. In addition, the difficulty in proving its finite time stability also impedes the expansion of this method. This article proposes an extended STA method based on homogeneity theory for Buck type DC/DC converters with uncertainty. Firstly, the STA method is extended to second-order systems, and finite time stability proof is provided based on homogeneity theory. By comparing with homogeneous second-order sliding mode and ordinary

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sliding mode control methods, the superiority of the proposed extended STA in combating uncertainty is demonstrated.

II. Digital Modeling

According to reference [10], the main circuit structure of the Buck converter is shown in Figure 1. Where, D is the freewheeling diode, $R$is the output load resistance, and S_w is the power switch transistor, C is the circuit output capacitor, L is the power inductor, and i_L is the inductive current, $i_C$is the capacitance current, V_o is the output voltage, V_{in} is the input voltage, u is the controller input which is the duty cycle of the switching transistor S_w satisfying $u \in [0,1]$. The Buck type step-down transformer achieves output voltage convergence to the reference voltage and maintains stability by adjusting the duty cycle u of the power switch S_w.

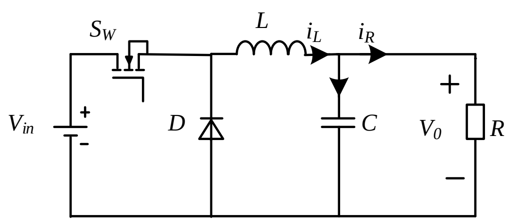

Fig. 1. Main circuit structure of Buck converter.

The state space model of Buck converter in continuous conduction mode can be represented as:

$$\begin{cases} \dot{V_o} = \frac{1}{C} i_C \\ \dot{i_C} = \frac{uV_{in}-V_o}{L} - \frac{\dot{V_o}}{R} \end{cases} \quad (1)$$

Define V_{ref} as the expected reference output voltage, and the state variable selected is the sliding surface $s = V_o - V_{ref}$ also known as the output voltage error, $\dot{s} = i_C$ is the output capacitor current, then:

$$\begin{bmatrix} \dot{s} \\ \ddot{s} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{LC} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} s \\ \dot{s} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{V_{in}}{LC} \end{bmatrix} v + \begin{bmatrix} 0 \\ \frac{V_{ref}}{LC} \end{bmatrix} \quad (2)$$

III. Controller Design

Based on the theory of homogeneity, an extended STA to second-order systems and its finite time stability proof is given below.

The most important property of a control system is whether it is stable. Unstable systems are generally unusable and also pose risks. The Lyapunov direct method, as the most classic criterion for stability analysis of nonlinear systems, is the most important tool for nonlinear system analysis and design. The advantages of this method are evident, as it only requires constructing a relevant positive definite energy function for the system, taking the derivative of this function, and based on the information of the derivative, one can determine whether the system is stable, exponentially stable, or globally asymptotically stable. This method clearly and intuitively demonstrates the concept of stability. And there is no need to linearize or perform various transformations on the system, and this method can also be directly used for controller design.

Lemma 1 : (Lyapunov theorem for global stability)[11]:

Assuming the existence of a scalar function V with state x, which has a first-order continuous partial derivative and

(1) $V(x)$ positive definite;

(2) $\dot{V}(x)$Negative definite;

(3) When $\|x\| \to \infty$, $V(x) \to \infty$;

So the origin as the equilibrium point is globally asymptotically stable.

The previous methods of control analysis and synthesis belong to infinite time stable control problems. From the perspective of control time optimization, the control method that makes the closed-loop system finite time stable is the time optimal and has important theoretical and practical research significance.

Consider the following system:

$$\dot{x} = f(x) \qquad f(0) = 0 \quad (3)$$

where $x \in R^n$, $x(0) = x_0$, $D \to R$ continuous with respect to x within an open area neighborhood D containing the origin $x = 0$.

Definition 1: For system (3), if there exists an open neighbourhood $U \subseteq D$ containing the origin $x = 0$ and a function $T_x\colon U\backslash\{0\} \to (0, \infty)$, such that for the existence of $x_0 \in U$, when $t \in [0, T(x_0))$, $x(t, x_0)$is defined and unique in forward time, satisfying equation $\lim_{t \to T_x(x_0)} x(t, t_0) = 0$, then the equilibrium point $x = 0$ of the system is finite time stable; When $t > T(x_0)$, there is $x(t, x_0) = 0$. The equilibrium point $x = 0$ is finite time stable if and only if it is Lyapunov stable, and if $U = D = R^n$, then the equilibrium point $x = 0$ is globally finite time stable.

Lemma 1: Assuming that a vector field can be divided into several vector fields, i.e. $f = g_1 + \cdots + g_k$. For each$i = 1, \ldots k$, the vector field is continuous and has a negative degree of homogeneity m_i. And $m_1 < m_2 < \cdots < m_k$. If in the vector field g_1 the origin is a finite time stable equilibrium point, then in the vector field f the origin is a finite time stable equilibrium point[12].

Lemma 2: (Finite time stability theorem for homogeneous systems) [13]: If a system is globally asymptotically stable and has negative homogeneity, i.e. $d < 0$, then the system is globally finite time stable.

Consider a type of second-order nonlinear system as follows:

$$\begin{cases} \dot{x}_1 = x_2^m \\ \dot{x}_2 = u \end{cases} \quad (4)$$

where x_1 and x_2 are system states, m is a positive odd number, the control objective is to control the input u to make the system converge to the origin within a finite time.

Here, the following second-order sliding mode control inputs based on homogeneity theory are adopted:

$$u = -l_1 \mathrm{sgn}(x_1)|x_1|^{\alpha_1} - l_2 \mathrm{sgn}(x_2)|x_2|^{\alpha_2} \tag{5}$$

where $l_1 > 0, l_2 > 0, 0 < \alpha < 1/m, \alpha_2 = \frac{(m+1)\alpha_1}{1+\alpha_1}$.

Theorem 1: For a class of second-order nonlinear systems (4), when the control input satisfies equation (5), the system (4) converges to the origin in finite time.

Proof: The proof of Theorem 1 involves two steps, first proving the asymptotic stability of the system.

Substitute the control law (5) into the system (4) to obtain the following closed-loop system equation:

$$\begin{cases} \dot{x}_1 = x_2^m \\ \dot{x}_2 = -l_1 \mathrm{sgn}(x_1)|x_1|^{\alpha_1} - l_2 \mathrm{sgn}(x_2)|x_2|^{\alpha_2} \end{cases} \tag{6}$$

Take Lyapunov function as:

$$V(x_1, x_2) = \frac{l_1|x_1|^{\alpha_1+1}}{\alpha_1+1} + \frac{|x_2|^{m+1}}{m+1} \tag{7}$$

Taking the derivative of (7) yields:

$$\dot{V} = -l_2|x_2|^{m+\alpha_2} \le 0 \tag{8}$$

Obviously, $\dot{V}$ negative semidefinite, V is non increasing and has a finite limit.

So state x_1 and x_2 are bounded. At this point ,take the derivative of $\dot{V}$ can lead to

$$\ddot{V} = -l_2(m + \alpha_2)|x_2|^{m+\alpha_2-1} \mathrm{sgn}(x_2) \tag{9}$$

Because of $m + \alpha_2 - 1 > 0, x_2$ is bounded, hence $\ddot{V}$ is bounded.

Then $\dot{V}$ uniform continuity, from Barbarat's lemma $\dot{V} \to 0$, then $x_2 \to 0$.

Then $\dot{x}_1$ and $\dot{x}_2$ are bounded, hence x_1 and x_2 are uniform continuity.

Take function $g = x_1 x_2$, Due to x_1 is bounded, $x_2 \to 0$, then there is a finite limit of 0 for g.

$$\dot{g} = -l_1|x_1|^{\alpha_1+1} - l_2 x_1|x_2|^{\alpha_2} \mathrm{sgn}(x_2) + x_2^2 = g_1 + g_2 \tag{10}$$

where $g_1 = -l_1|x_1|^{\alpha_1+1}, g_2 = -l_2 x_1|x_2|^{\alpha_2} \mathrm{sgn}(x_2) + x_2^2$, $\dot{g}_1 = -l_1(a_1 + 1)|x_1|^{\alpha_1}$, $\dot{g}_1$ is bounded, therefore g_1 is continuous, then $\dot{g}$ is continuous, therefore according to Barbarat's lemma $\dot{g} \to 0$. And because of $x_2 \to 0$, so $g_2 \to 0$, and then $g_1 \to 0$, $x_1 \to 0$.

It can be seen that the closed-loop system is asymptotically stable.

Next, verify that the system has negative homogeneity.

Define vector field:

$$f = [f_1(x_1, x_2), f_2(x_1, x_2)]^T \tag{11}$$

where $f_1(x_1, x_2) = x_2^m$, $f_2(x_1, x_2) = -l_1 \mathrm{sgn}(x_1)|x_1|^{\alpha_1} - l_2 \mathrm{sgn}(x_2)|x_2|^{\alpha_2}$

Homogeneous expansion:

$$\Delta_k: (x_1, x_2) \to (kx_1, k^{\frac{\alpha_1+1}{m+1}} x_2) \tag{12}$$

then

$$f_1\left(kx_1, k^{\frac{\alpha_1+1}{m+1}} x_2\right) = k^{\frac{m(\alpha_1+1)}{m+1}} x_2^m$$

$$= k^{1+\frac{m\alpha_1-1}{m+1}} x_2^m = k^{1+\frac{m\alpha_1-1}{m+1}} f_1(x_1, x_2) \tag{13}$$

$$f_2\left(kx_1, k^{\frac{\alpha_1+1}{m+1}} x_2\right)$$

$$= -l_1 \mathrm{sgn}(kx_1)|kx_1|^{\alpha_1} - l_2 \mathrm{sgn}\left(k^{\frac{\alpha_1+1}{m+1}} x_2\right)\left|k^{\frac{\alpha_1+1}{m+1}} x_2\right|^{\alpha_2}$$

$$= k^{\frac{\alpha_1+1}{m+1} + \frac{m\alpha_1-1}{m+1}} f_2(x_1, x_2) \tag{14}$$

Because of $0 < \alpha < 1/m$, so $k = (m\alpha_1 - 1)/(m + 1) < 0$.

It can be verified, take $r_1 = 1, r_2 = (\alpha_1 + 1)/(m + 1)$ and parameter values satisfying $0 < \alpha_1 < 1/m$, $\alpha_2 = (m + 1)\alpha_1/(1 + \alpha_1)$, the homogeneity of the system is $k = (m\alpha_1 - 1)/(m + 1) < 0$, the system is globally asymptotically stable and has negative homogeneity, According to Lemma 2, the system is globally finite time stable.

Theorem 2: Consider a class of second-order systems:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = u \end{cases} \tag{15}$$

where $x_i \in R$, $u \in R$ are the system state and control inputs, respectively.

The controller:

$$\begin{cases} u = -\lambda_1|x_1|^a \mathrm{sgn}(x_1) - \lambda_2|x_2|^b \mathrm{sgn}(x_2) + x_3 \\ \dot{x}_3 = -\alpha \mathrm{sgn}(x_2) \end{cases} \tag{16}$$

can make the system states x_1 and x_2 converge to the origin simultaneously in finite time.

where λ_1, λ_2 and α are all positive constants, $b = \frac{2a}{1+a}$, $0 < b < \frac{1}{2}$.

Proof: Substitute (16) into (15) to obtain the system as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\lambda_1|x_1|^a \mathrm{sgn}(x_1) - \lambda_2|x_2|^b \mathrm{sgn}(x_2) + x_3 \\ \dot{x}_3 = -\alpha \mathrm{sgn}(x_2) \end{cases} \tag{17}$$

The vector field f on the right side of equation (17) can be regarded as the sum of two homogeneous vector fields:

$$f = g_1 + g_2 \tag{18}$$

where

$$g_1 = [x_2, -\lambda_1|x_1|^a \mathrm{sgn}(x_1) - \rho\lambda_2|x_2|^b \mathrm{sgn}(x_2), 0] \tag{19}$$

$$g_2 = [0, -(1 - \rho)\lambda_2|x_2|^b \mathrm{sgn}(x_2), -\alpha \mathrm{sgn}(x_2)] \tag{20}$$

First, for the finite time stability property of the vector field g_1, take the Lyapunov function:

$$V(x_1, x_2) = \frac{\lambda_1|x_1|^{a+1}}{a+1} + \frac{|x_2|^2}{2} \tag{21}$$

Taking the derivative of equation (21) yields:

$$\dot{V} = \lambda_1|x_1|^a \dot{x}_1 \mathrm{sgn}(x_1) + x_2\dot{x}_2$$
$$= \lambda_1|x_1|^a x_2 \mathrm{sgn}(x_1) + x_2[-\lambda_1|x_1|^a \mathrm{sgn}(x_1) - \rho\lambda_2|x_2|^b \mathrm{sgn}(x_2)]$$
$$= -\rho\lambda_2|x_2|^{b+1} \tag{22}$$

Obviously, $\dot{V}$ is Negative semidefinite; V is non increasing and has a finite limit.

So states x_1 and x_2 are bounded. At this point, taking the derivative of $\dot{V}$ leads to

$$\ddot{V} = -\rho\lambda_2(b+1)|x_2|^b \mathrm{sgn}(x_2) \tag{23}$$

Since $0 < b < \frac{1}{2}$ and x_2 is bounded, $\ddot{V}$ is bounded.

So $\dot{V}$ is uniformly continuous, and according to Barbarat's lemma, $\dot{V} \to 0$, then $x_2 \to 0$.

Select function $m = x_1x_2$, since x_1 is bounded and $x_2 \to 0$, m has a finite limit 0.

$$\dot{m} = -\lambda_1|x_1|^{a+1} - \rho\lambda_2 x_1|x_2|^b \mathrm{sgn}(x_2) + x_2^2 = m_1 + m_2 \tag{24}$$

where $m_1 = -\lambda_1|x_1|^{a+1}, m_2 = -\rho\lambda_2 x_1|x_2|^b \mathrm{sgn}(x_2) + x_2^2$, $\dot{m}_1 = -\lambda_1(a+1)|x_1|^a$, $\dot{m}_1$ is bounded, therefore m_1 is continuous, then $\dot{m}$ is continuous. Therefore according to Barbarat's lemma $\dot{m} \to 0$. Since $x_2 \to 0, m_2 \to 0$, then $m_1 \to 0$, therefore $x_1 \to 0$.

It can be seen that the closed-loop system is asymptotically stable.

Let's take another look at the homogeneity of the vector field g_1, let's make the vector field:

$$g_1 = [h_1(x_1,x_2,x_3), h_2(x_1,x_2,x_3), h_3(x_1,x_2,x_3)]^T \tag{25}$$

where,

$$h_1(x_1,x_2,x_3) = x_2 \tag{26}$$
$$h_2(x_1,x_2,x_3) = -\lambda_1|x_1|^a \mathrm{sgn}(x_1) - \rho\lambda_2|x_2|^b \mathrm{sgn}(x_2) \tag{27}$$
$$h_3(x_1,x_2,x_3) = 0 \tag{28}$$

Homogeneous expansion:

$$\Delta_\mathrm{k}: (x_1,x_2,x_3) \to (kx_1, k^{\frac{a+1}{2}}x_2, \mathrm{k}x_3) \tag{29}$$

Then

$$h_1\left(kx_1, k^{\frac{a+1}{2}}x_2, \mathrm{k}x_3\right) = k^{\frac{a+1}{2}}x_2 = k^{1+\frac{a-1}{2}}h_1(x_1,x_2,x_3) \tag{30}$$

$$h_2\left(kx_1, k^{\frac{a+1}{2}}x_2, kx_3\right) = -\lambda_1 \mathrm{sgn}(kx_1)|kx_1|^a - \rho\lambda_2 \mathrm{sgn}\left(k^{\frac{a+1}{2}}x_2\right)\left|k^{\frac{a+1}{2}}x_2\right|^b = k^{\frac{a+1}{2}+\frac{a-1}{2}}h_2(x_1,x_2) \tag{31}$$

$$h_3\left(kx_1, k^{\frac{a+1}{2}}x_2, \mathrm{k}x_3\right) = 0 = k^{1+\frac{a-1}{2}}h_3(x_1,x_2,x_3) \tag{32}$$

Because $0 < a < 1$, then $\frac{a-1}{2} < 0$.

Therefore, the system is asymptotically stable and has negative homogeneity. According to Lemma 2, the system is globally finite time stable. The system is stable for a limited time $[x_1,x_2,x_3] = [0,0,x_3(0)]$.

Vector field g_2 is equivalent to the Super-twisting algorithm, which makes the system finite time stable at $[x_{1f},0,0]$. Its stability proof can be seen in reference [14] and [15].

Make vector field:

$$g_2 = [h_4(x_1,x_2,x_3), h_5(x_1,x_2,x_3), h_6(x_1,x_2,x_3)]^T \tag{33}$$

where,

$$h_4(x_1,x_2,x_3) = 0 \tag{34}$$
$$h_5(x_1,x_2,x_3) = -(1-\rho)\lambda_2|x_2|^b \mathrm{sgn}(x_2) \tag{35}$$
$$h_6(x_1,x_2,x_3) = -\alpha \mathrm{sgn}(x_2) \tag{36}$$

Homogeneous expansion:

$$\Delta_k: (x_1,x_2,x_3) \to (kx_1, kx_2, \mathrm{k}^{1-\mathrm{b}}x_3) \tag{37}$$

Then

$$h_4(kx_1,kx_2,k^{1-b}x_3) = 0 = k^{1+(b-1)}h_4(x_1,x_2,x_3) \tag{38}$$
$$h_5(kx_1,kx_2,k^{1-b}x_3) = -(1-\rho)\lambda_2|kx_2|^b \mathrm{sgn}(kx_2) = \mathrm{k}^{1+(b-1)}h_5(x_1,x_2) \tag{39}$$
$$h_6(kx_1,kx_2,k^{1-b}x_3) = -\alpha \mathrm{sgn}(kx_2) = k^{1-b+(b-1)}h_6(x_1,x_2,x_3) \tag{40}$$

Because $0 < b < 1$, so $b - 1 < 0$.

Therefore, the system is asymptotically stable and has negative homogeneity. According to the finite time stability theorem of homogeneous systems, g_2 makes the system stable at a finite time $[x_1,x_2,x_3] = [x_{1f},0,0]$.

According to Lemma 1, when the homogeneity of g_1 is less than that of g_2, let $x_3(0) = 0$. The algorithm proposed here ensures that the system is finite time stable at the origin.

IV. Simulation Analysis

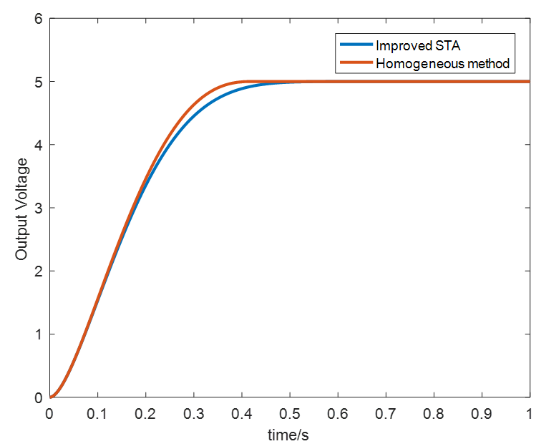

Fig. 2. Simulation results.

In the simulation, the parameters of the Buck converter model are taken as the input voltage $V_{in} = 17$V, reference output voltage $V_{ref} = 5$V, rated resistance R=10 Ω, rated inductance L=100 μH and the rated capacitance C=1000 μF.

Initial values of system states variable $V_o(0) = 0$, $i_C = 0$. Firstly, compared with the homogeneous second-order sliding mode control method [13] and these two controllers take the same parameters: $\lambda_1 = 10, \lambda_2 = 10, \alpha = 0.2$.

The simulation results are shown in Figure 2.

If disturbances were added at the beginning of the system operation, simulation results are shown in Figure 3:

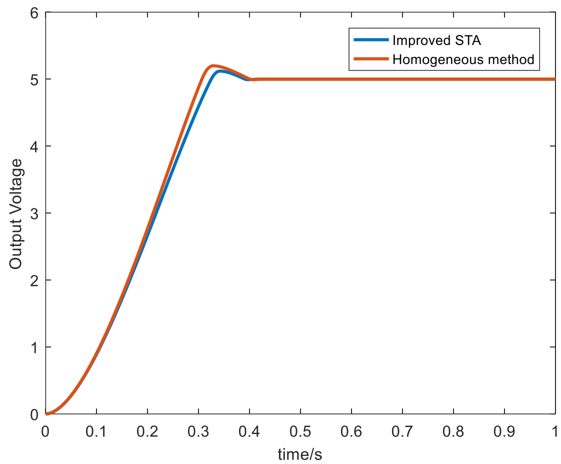

Fig. 3. Simulation results under disturbances at the beginning.

It can be seen that our proposed extended STA has a lower overshoot than the homogeneous method.

If disturbances occur in the plateau period of operation, the simulation results are shown in Figure 4:

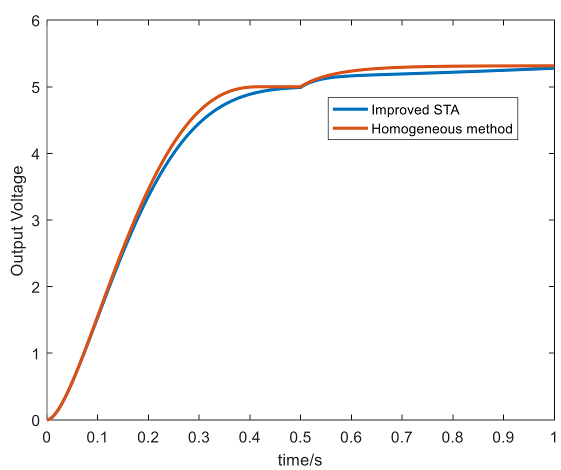

Fig. 4. Simulation results under disturbances during operation.

From Figure 4, it can be seen that our proposed extended STA performs better than the homogeneous method.

Next, compared our extended STA with traditional sliding mode control methods, sliding mode control exhibits chattering in the system due to its inherently discontinuous switching characteristics. According to the traditional definition of sliding mode control, select the sliding mode surface: $s_1 = s + k\dot{s}$. The system control law is $v_1 = -\varepsilon_1 \mathrm{sgn}(s_1) - k_1 s_1$. Take control parameters in simulation, $k = 1, \varepsilon_1 = 500, k_1 = 1000$. The proposed extended STA controller parameters are: $\lambda_1 = 18, \lambda_2 = 16, \alpha = 0.2$. The simulation results are shown below:

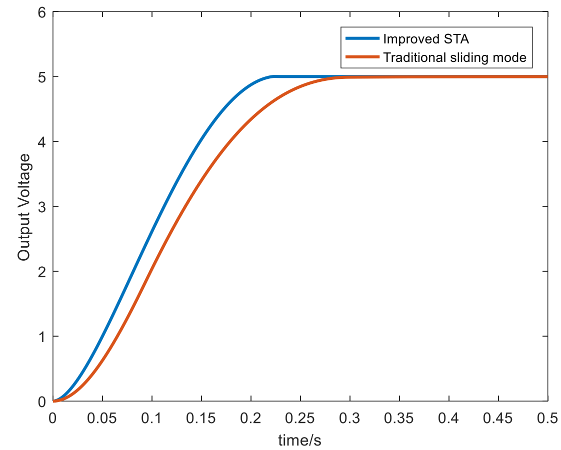

Fig. 5. Simulation results.

At the beginning of the system operation, disturbances were added, and the simulation results are shown in Figure 6:

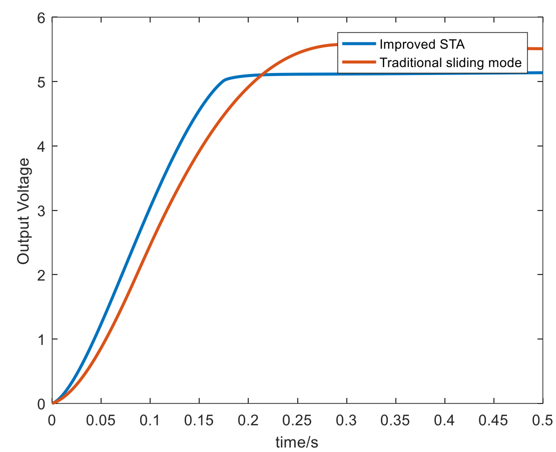

Fig. 6. Simulation results under disturbances at the beginning.

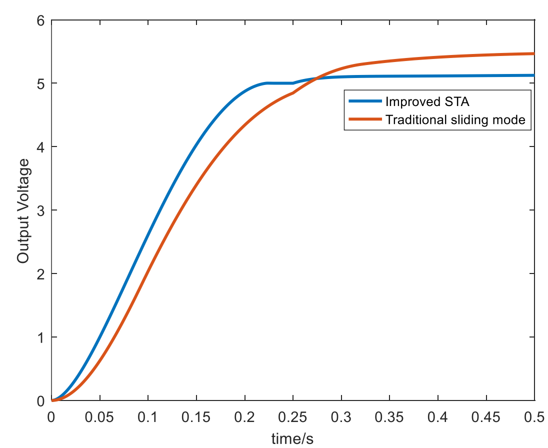

Fig. 7. Simulation results under disturbances during operation.

It can be seen that the original sliding mode control algorithm is divergent, our proposed extended STA can still maintain good performance.

If disturbances occur in the plateau period of operation, the simulation results are shown in Figure 7:

From Figure 7, it can be seen that the proposed method performs better than the traditional sliding mode control method while the original method diverges.

V. Conclusion

To improve the dynamic performance and robustness of Buck circuit control systems, a finite time robust control method for Buck circuits based on high-order sliding mode control is proposed and it not only rapidly stabilizes the output voltage within a limited time, but also has a certain degree of robustness to system uncertainty. The simulation results have verified the effectiveness and advantages of the proposed method by comparing it with traditional sliding mode control and second-order homogeneous sliding mode control methods, especially, in its obvious superiority in combating uncertainty.

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