Super Twisting Observer based Second Order Sliding Mode Control for Power Converter with Disturbance

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Abstract— **Sliding mode control (SMC) has been widely used in DC-DC power converters due to its insensitivity the disturbances. In this paper, a super twisting observer-based second-order sliding mode controller is proposed for a buck converter with matched disturbance. First, the matched and mismatched disturbances due to load resistance and input voltage variations are transformed into a single matched total disturbance. Second, a super twisting observer (STO) is designed to estimate the states of a buck converter with matched disturbance in finite time. Then, the second-order sliding mode controller (SOSMC) is constructed utilizing a sliding surface with estimated states. The proposed controller and STO are tested using simulations with varying input voltage and load. The simulation results for the suggested technique show that reference tracking performance is effective in the presence of matched disturbances. The chattering is also decreased. The proposed controller enhances robustness to disturbances and uncertainty as well as dynamic performance.**

Keywords—DC-DC converters, observer, SMC, disturbance, super twisting

I. INTRODUCTION

DC-DC power converters are widely used in renewable energy generation, wind systems, fuel cell systems, telecommunications systems, DC motor drive, electric vehicles, and DC microgrids. DC-DC power converters achieve a desired constant output voltage in voltage regulation applications despite the disturbances in the input voltage or load. The outputs of converters connected to these applications degrade as a result of environmental factors, internal uncertainties, and load conditions. The purpose of the controllers in these systems is to keep the system under a constant output voltage despite external disturbances or internal dynamic uncertainties. Many techniques for controlling DC-DC power converters, such as PI control which linear control method, fuzzy logic control [1], backstepping control [2], model predictive control [3], H_∞ control [4] and robust control [5] have been investigated [6]. PI controllers, despite their ease of application and parameter adjustment, are unable to match the requirements in the presence of uncertainty and disturbances. Although existing nonlinear control systems have been proved to be somewhat successful, numerous difficulties remain unsolved, including controller design and tuning simplicity, robustness to load variations. Furthermore, although the preceding control approaches tackle some of the existing problems, they cannot deal with disturbances quickly and actively, and it is difficult to obtain rapid and accurate voltage output performance in closed-loop systems with lumped disturbances.

Sliding mode control (SMC) outperforms other methods in systems with uncertainties and disturbances. SMC is a nonlinear control method with simplicity, robustness, and fast dynamic responses [7]. One of the most common methods for designing controllers, SMC conforms to the nature of variable structure DC-DC converters. Because of its degree reduction, high dynamic performance, and robustness against disturbances and parameter changes, it has been the approach of choice for sliding mode control (SMC) power converters [8].

DC-DC power converters are well-known to be variable-structure nonlinear and time-varying systems [9]. Converters are nonlinear components due to their variable switching frequency and can be controlled by SMC. However, the disadvantage of SMC is that it has chattering due to the signum function in the control rule and variable switching frequency [10]. Second-order sliding mode (SOSM), a type of high-order sliding mode control, has been introduced to reduce chattering and ensure high control performance for a system [11]. In the SOSMC, the sliding surface (σ) and its derivative ($\dot{\sigma}$) are continuous, while the second derivative of the sliding surface ($\ddot{\sigma}$) is discontinuous. SOSMC algorithms have been discussed to regulate the buck converter system's output voltage to the desired reference voltage [12].

SMC theory studies have revealed significant benefits of adopting specific dynamics into sliding mode controllers [13]. This new approach, called observer-based SMC, simulates the ideal plant model of the sliding mode controller in parallel with the real one [10]. In general, an observer may be thought of as an additional dynamic system that is inserted artificially to enhance control performance.

The sliding surfaces in the conventional SMC approach must be of relative degree one. The conventional SMC, when applied to a buck converter, requires that the sliding surface is by a combination of the output voltage/or inductor current and the capacitor current. Several sensors that measure all output states are required to implement SMC. However, sensors to detect these states are not widely available in many systems, which increases the overall cost of the system. Sliding mode observer is one of the most effective methods for estimating the system's state. The sliding mode observer derives the value of the unknown state variable from the input and known state variable outputs. The Sliding mode observer also aids in minimizing chattering, which is a challenge to SMC [14]. Furthermore, their well-known benefits include robustness and insensitivity to external disturbance.

It is not possible to use classical observers to derive unknown states from the given output. The sliding mode observer derives the value of the unknown state variable from the input and known state variable values [15]. Super twisting observer (STO) outperform traditional sliding mode-based observers because their output is continuous and does not need filtering [16]. In this study, STO is proposed for estimating the state and its derivatives without the use of extra sensors.

In this paper, a super twisting observer-based second-order sliding mode offers a controller with only output voltage measurement for buck converters with matched disturbance. The proposed control scheme is eliminated load resistance disturbance and input voltage variations. First, a super twisting observer using the information of only the output voltage is designed to give information about unmeasurable states. Second, taking the error variable of the estimate of the output voltage value and the reference value as the sliding surface directly, a controller with second-order sliding mode control law is proposed for the DC-DC buck converter. Then, the output voltage is designed using SMC to track the desired reference voltage. The simulation results show that the proposed control strategy increases the system's tracking performance as well as its robustness against disturbances and uncertainty. Meanwhile, the approach does not require a current sensor and instead relies only on a voltage sensor. As a result, the cost of practical application is reduced.

The rest of this paper is organized as follows. In Section II, introduces the system model of buck converters and the purposes of STO-based SOSMC are presented. The design procedure of the STO-based second-order sliding mode controller is given in Section III, including the controller design and observer design. In Section IV, simulation results are shown to validate the effectiveness of the proposed method. Finally, conclusions are given in Section V.

II. DYNAMIC MODEL OF DC/DC BUCK CONVERTER

Buck converters are common DC-DC converters that convert high input voltages to low output voltages. The buck converter consists of a DC input voltage source (v_{in}), a control switch (S), a diode (D), a circuit capacitor (C), an inductor (L), and load resistance (R). Fig. 1 shows a DC-DC buck converter, in which i_L is the inductor current; i_R is the output current and v_o is the output voltage. In practice, load resistance varies continually with operational temperature and there are fluctuations at the input voltage source. The nominal values of load resistance and input voltage are defined as R_o and v_{ino} respectively.

When the switch is turned on, current flows as shown by (blue dashed line 1) in Fig. 1, and the output voltage and inductor current equations are as follows:

$$v_{in} = L\frac{di_L}{dt} + v_o \tag{1}$$

$$C\frac{dv_o}{dt} = i_L - \frac{v_o}{R} \tag{2}$$

When the switch is turned off, current flows as shown by (blue dashed line 2) in Fig. 1, and the output voltage and inductor current equations are as follows:

$$L\frac{di_L}{dt} = v_o \tag{3}$$

$$C\frac{dv_o}{dt} = i_L - \frac{v_o}{R} \tag{4}$$

Then, the dynamic model of the system may be stated as [17]

$$\frac{di_L}{dt} = \frac{v_{in}}{L}u - \frac{v_o}{L} \tag{5}$$

$$\frac{dv_o}{dt} = \frac{i_L}{C} - \frac{v_o}{RC} \tag{6}$$

The controller's purpose is to set the output voltage of the buck converter to the desired reference voltage (v_{ref}). The output voltage is expressed as

$$x_1 = v_o \tag{7}$$

Equations (5 and 6) are rewritten as

$$\dot{x}_1 = x_2 \tag{8}$$

$$\dot{x}_2 = \frac{v_{ino}}{LC}u - \frac{x_1}{LC} - \frac{x_2}{R_oC} + d_1 \tag{9}$$

where $d_1 = \frac{v_{in}}{LC}u - \frac{v_{ino}}{LC}u + \frac{x_2}{R_oC} - \frac{x_2}{RC}$.

The following are the aims outlined in this paper:

- The output voltage should be traced to the reference value, that is $x_1 \rightarrow v_{ref}$
- The derivative of output voltage produced by the observer should be traced to the x_2, that is $x_2 \rightarrow \dot{v}_o$
- The output current should track the reference current (i_{Lref}).
- The impacts of parametric uncertainties and external disturbances should be reduced by the controller.

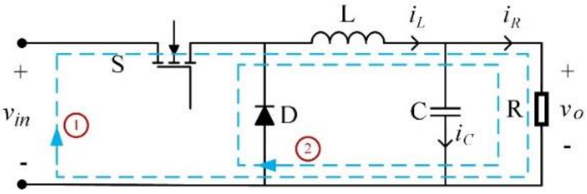

Fig. 1. DC-DC buck converter

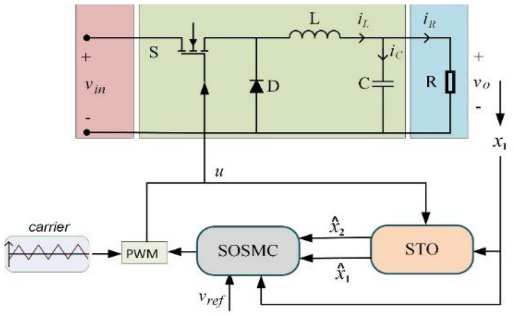

Fig. 2. Control Structure of the STO based SOSMC for the buck converter

III. CONTROLLER AND OBSERVER DESIGN

The STO-based SOSMC structure is shown in Fig. 2. Firstly, STO predicts both disturbances and system states using only the output voltage. Then, based on this estimated output voltage and its derivative value, a sliding surface is designed. Furthermore, a control signal (u) is derived from the second-order sliding mode controller utilizing these predicted values. Finally, the control signal is compared to sawtooth waves, and a PWM signal is created to drive the switch of the DC-DC buck converter.

A. Super Twisting Observer Design

This subsection aims to build an STO for identifying total disturbances induced by changes in input voltage and load resistance. The STO is described by Eqs. (10-11)

$$\dot{\hat{x}}_1 = \hat{x}_2 + k_1|\tilde{x}_1|^{\frac{1}{2}}sign(\tilde{x}_1) \tag{10}$$

$$\dot{\hat{x}}_2 = \frac{v_{in}}{LC}u - \frac{x_1}{LC} - \frac{\hat{x}_2}{RC} + d1 + k_2sign(\tilde{x}_1) \tag{11}$$

where $\hat{x}_{1,2}$ are defined as the estimated values of system state variables. Let's define error variables as $\tilde{x}_{1,2} = x_{1,2} - \hat{x}_{1,2}$. $k_{1,2}$ are the observer gains. The estimate errors are given by

$$\dot{\tilde{x}}_1 = \tilde{x}_2 + k_1|\tilde{x}_1|^{\frac{1}{2}}sign(\tilde{x}_1) \tag{12}$$

$$\dot{\tilde{x}}_2 = -\frac{\tilde{x}_2}{RC} - k_2sign(\tilde{x}_1) + d_1 \tag{13}$$

Suppose that the system states can be considered to be bounded. Let k_1 and k_2 satisfy the inequalities follows as [18]

$$z > \left|F(t, x_{1,}x_2\hat{x}_2)\right| \tag{14}$$

$$k_1 > z \tag{15}$$

$$k_2 > \sqrt{\frac{2}{a-}\frac{(k_1+z)(1+\rho)}{(1-\rho)}}, \quad (0 < \rho < 1) \tag{16}$$

B. Second Order Sliding Mode Controller Design

The ability of SMC to entirely reject bounded matched perturbation is its most essential property. However, the main disadvantage of classical SMC is the chattering that resulted from the existence of the discontinuous switch function [19]. The simplest and most used method for reducing chattering is to utilize various functions such as saturation and sigmoid instead of the discontinuous sign function. Second-order SMC algorithms such as super twisting [20] and twisting [21] prescribed convergence law [22], have also been proposed in the literature to reduce the chattering effect to buck converter. Let the dynamical system be described as

$$\dot{x} = Ax + Bu \tag{17}$$

The SOSMC control rule is defined as u, and the estimated sliding surface is defined as

$$\hat{\sigma} = x_1 - v_{ref} \tag{18}$$

$$\ddot{\hat{\sigma}} = h(t,x) + g(t,x)u \tag{19}$$

where $h(t,x)$ and $g(t,x)$ are smooth uncertain functions. In the second-order sliding mode control, unlike the classical sliding mode control, the control effort is directly related to the second derivative of the sliding surface, the sign and the size of the sliding surface. The controller's switching rule based on the prescribed convergence law is as follows:

$$u = 0.5\left(1 - \alpha sign\left(\dot{\hat{\sigma}} + \beta|\hat{\sigma}|^{\frac{1}{2}}sign(\hat{\sigma})\right)\right) \tag{20}$$

IV. SIMULATIONS RESULTS

Simulation results were obtained for testing the dynamic performance of the proposed method under step changes in the load, the input voltage, and the reference output voltage. The simulation verification in this research is based on Matlab / Simulink. Table 1 displays the parameters of the proposed controller as well as the DC-DC buck converter parameters. To test the disturbance rejection ability of STO-based SOSMC, two different types of disturbances similar to the actual DC-DC buck converter have been studied. The first is a change in load resistance, while the second is a change in input voltage. At 0.015s the load resistance changes from 10 Ω to 15 Ω. Furthermore, the input voltage changes are configured to vary from 24 V to 20 V, and then, the input voltage is changed from 12 V to 9 V.

TABLE I. SIMULATION PARAMETERS

Parameters	**Values**
Input voltage (v_{in})	20 V-24 V
Reference voltage (v_{ref})	12 V
Switching frequency (f_s)	100 kHz
Inductor (L)	160 μH
Capacitor (C)	15 μF
Load (R)	8-25 Ω
α, β	$1, 10^4$
k_1, k_2	$10^3, 10^3$

Fig. 3 shows the simulated responses of the output voltage (v_o) and its estimation ($\hat{x}_1$) in constant input voltage and constant load. It is clear from Fig. 3 that the $\hat{x}_1$ is exactly followed the v_o. Fig.4 displays the simulated responses to the derivative of output voltage ($\dot{v}_o$) and its estimate ($\hat{x}_2$). Here, it should be noted that although the observer functions perfectly, the sign(x) causes chattering. Fig. 5 shows the simulated responses of estimated errors together with the $\tilde{x}_1$ versus $\tilde{x}_2$ trajectory. It is obvious that there are no estimation errors. Fig. 6 depicts the evolution of the sliding surface to time. It is clear from Fig. 6 that the sliding surface approaches zero. The system's required parameters are appropriately constructed by the designed super twisting observer. The output voltage of the converter converges to the reference voltage when the approach given in this paper is used.

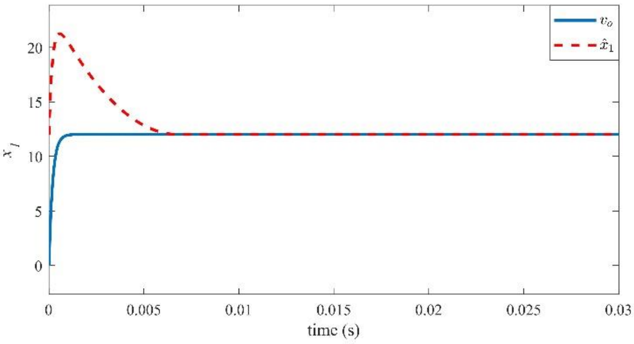

Fig. 3. The output voltage and its estimate

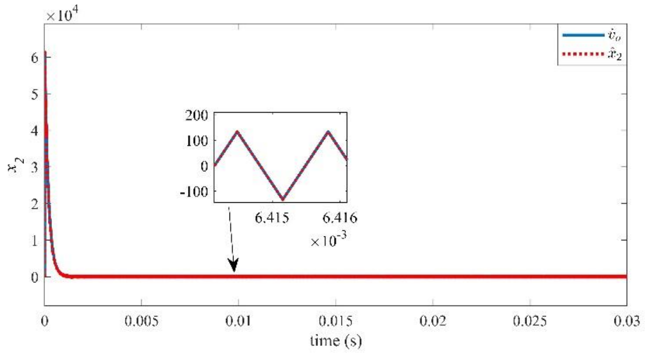

Fig. 4. The derivative output voltage and its estimate

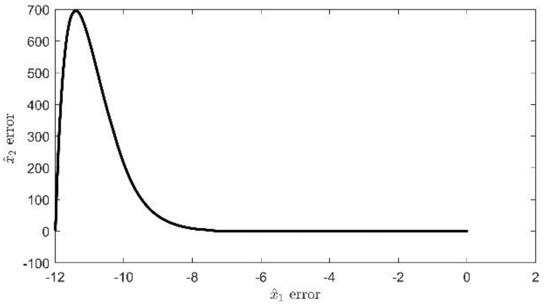

Fig. 5. The estimation errors $\tilde{x}_1$ versus $\tilde{x}_2$

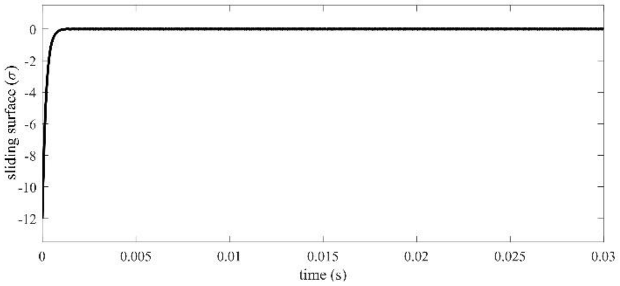

Fig. 6. The sliding surface

During start-up, the load is set to $R = 10\,\Omega$. Step changes in load are considered a disturbance. Fig. 7 shows simulation graphs for output voltage while load resistance is changed from $10\,\Omega$ to $15\,\Omega$ at $t = 0.015\,s$. The output voltage takes approximately 0.002 s to track its reference. The voltage difference is less than 2 millivolts. It can be seen from Fig. 8 that the controller keeps track of its reference by decreasing the output current while keeping the output voltage constant. It is obvious from Figs. 7-8 that the outputs track its references successfully. The plot of generated PWM pulses that operate as a control input to the converter switch is shown in Fig. 9. The duty cycle remains constant, as seen in Fig. 9.

The simulated state trajectories of the converter, due to the step-change in load from $10\,\Omega$ to $15\,\Omega$, are shown in Fig. 10. It can be seen from Fig. 10 that the trajectories converge to zero. Furthermore, as seen in Fig. 11, the estimation error is zero. Fig. 12 shows the simulation responses of the output voltage and the inductor current for the start-up and the step change in the input voltage from 24 V to 20 V. It can be seen from Fig.12 that the output voltage is almost not affected by the step-change in the input voltage. Fig. 13 depicts the variation in the duty cycle required to maintain a constant output voltage.

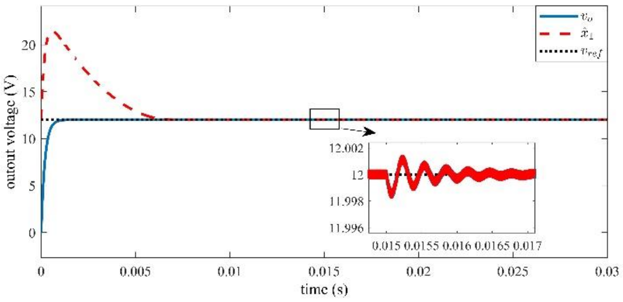

Fig. 7. The output voltage during load resistance change

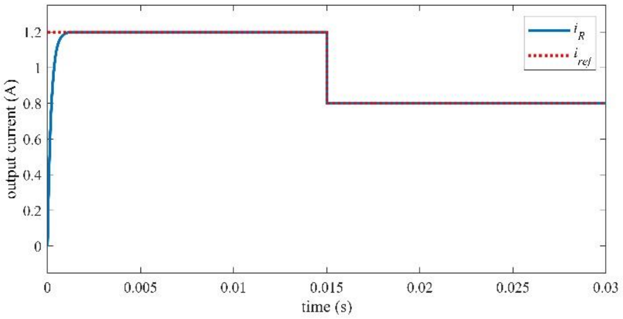

Fig. 8. The output current during load resistance change

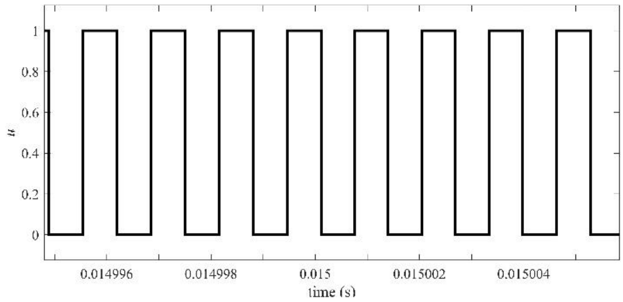

Fig. 9. The generated PWM pulses during load resistance change

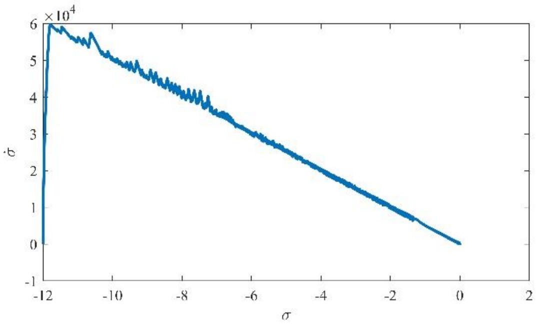

Fig. 10. The phase portrait of the buck converter

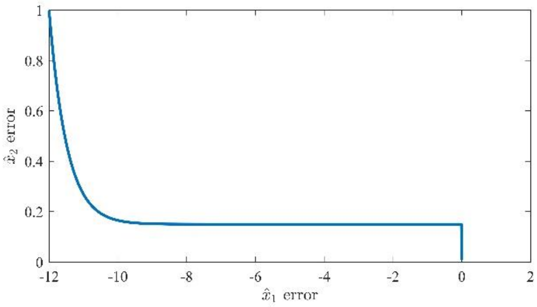

Fig. 11. The estimation errors during load resistance change

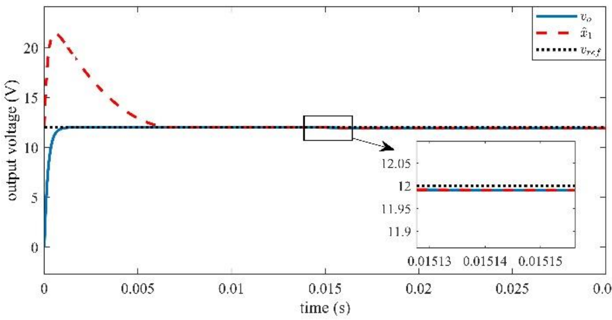

Fig. 12. The output voltage and its estimate during the input voltage change

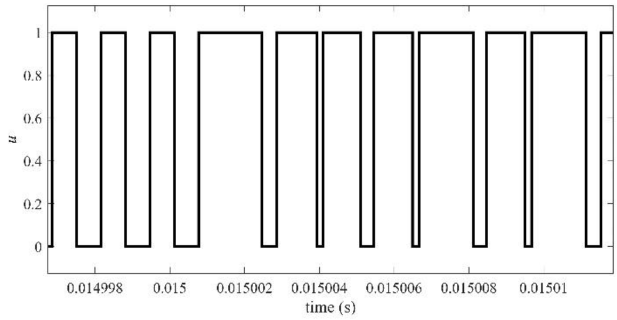

Fig. 13. The duty cycle during the input voltage change

Fig. 14 shows the response of the output voltage for step changes in the reference voltage from 12 V to 9 V. It is clear from Fig. 14 that the output voltage tracks successfully its reference faster (almost 1 ms). Fig. 15 displays that the output current tracks its reference value closely. The controller adjusts the duty cycle supplied to the switch to track the reference voltage, as shown in Fig 16. The results presented in the figures show that the STO-based SOSMC is very robust against input voltage change, load change, and reference voltage variations. Furthermore, the proposed super twisting observer accurately tracks state variables and their derivatives.

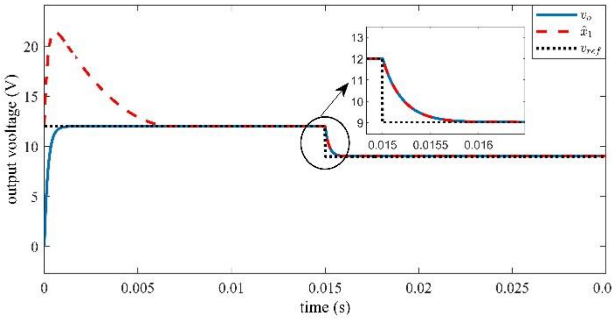

Fig. 14. The output voltage during the change in the reference voltage

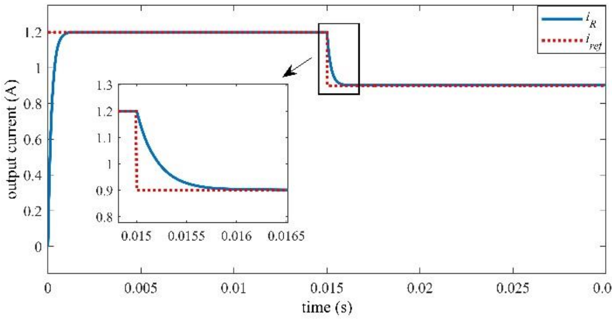

Fig. 15. The output current during the change in the reference voltage

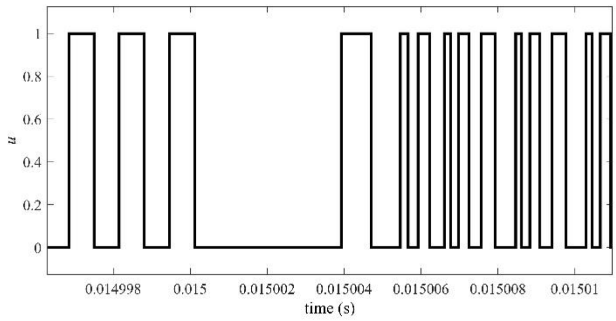

Fig. 16. The duty cycle during the change in the reference voltage

V. CONCLUSION

The super-twisting observer-based second-order sliding-mode controller was designed for a buck converter with matched disturbances. STO reduces estimating error to zero in finite time. With a smaller sensor number, it retains the properties of continuous control and finite-time convergence of the sliding variable and system states. Simulation validations are provided to demonstrate the effectiveness of the proposed control method, which provides quick reaction, zero steady tracking error, and high robustness in the face of uncertainties and disturbances. Furthermore, the switching control rule employs the second-order sliding mode control law, which eliminates chattering without reducing nominal performance.

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