Second-Order Sliding Mode Control Algorithms in DC/DC Buck Converter

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***Abstract*— DC/DC converters are widely used in new generation applications such as microgrid, electric vehicles, and storage systems. Controllers, which ensure the converters output voltage on the reference value, are designed with many different methods. Sliding mode control is a prominent controller design for power converters that has recently attracted the attention of researchers. Although the conventional sliding mode control has many advantages, chattering and relative degree restriction are its outstanding weaknesses. The second-order sliding mode control, which eliminates the disadvantages of the conventional sliding mode control, uses different algorithms according to the relative degree of the system controlled. Algorithm with prescribed convergence law, twisting algorithm and super twisting algorithm are commonly implemented second-order sliding mode control algorithms. In this paper, controllers using second-order sliding mode control algorithms have been designed for a DC/DC buck converter feeding a resistive load. Tests realized in the Matlab/Simulink environment have revealed the robustness and performance of the controllers designed different sliding mode controller algorithms under various operating scenarios such as input voltage variation and load variation. As a result of the simulations, the dynamic responses of these control algorithms have been analyzed and compared with each other and.**

Keywords—DC/DC converters, sliding mode control, twisting, super twisting, prescribed convergence law, chattering

I. INTRODUCTION

Various DC/DC power converter topologies are used to raise or decrease the output voltage levels of the electrical systems. Buck converters are one of the basic converters that are widely used in new generation applications such as energy storage systems, mobile power supplies, DC power supplies, microgrid applications, PV systems. Buck converters, which are components of DC/DC power electronics, have advantages such as simple structure, easy control and easy application [1,2]. Buck converters, also called step downs, are used to adjust the voltage level between source and load.

Controller design plays an important role in controlling the output voltage of buck converters. The most important purpose of these controllers is to be able to regulate the output voltage tightly according to the reference when any disturbance occurs in the system. The control signal is determined by applying the small-signal model of the converter and the frequency domain techniques [3]. After designing based on the small-signal model, the dynamic performance of the converter is determined only around a certain equilibrium point. Since the control design for buck converters is mostly based on a linear mathematical model, it is seen that conventional PI and PID controllers are widely applied. Such controller designs cause distorted output signals or unstable behavior of systems in large-signal disturbances [4]. Therefore, improving the control performance of converters against system uncertainties and disturbances becomes an important issue. As a result, controllers based on nonlinear control methods such as step-down converters artificial neural networks [5], adaptive control [6], and fuzzy logic [7] have been developed.

Buck converters are inherently non-linear power electronics components. One of the applications where sliding mode control (SMC) is used is the control of the output voltage of switched power converters. DC/DC converters are difficult to control with conventional control methods and those methods cause instability issues. Therefore, for nonlinear systems, the SMC method is used, which provides robust responses to parameter changes and external disturbances [8, 9]. SMC is one of the nonlinear control methods with some advantages such as being robust against parameter uncertainties, load distortion, fast dynamic response, and easy implementation [10, 11]. However, the most significant drawbacks of classical SMC are relative degree restriction and chattering. High order sliding mode control (HOSMC) techniques have been proposed to eliminate this difficulty [12, 13]. In addition, while HOSMC eliminates these disadvantages, it also incorporates the advantages of traditional SMC. The second-order sliding mode control (SOSMC) can be defined as a subset of SMC. If the system has a relative degree of two, it is called SOSMC [14]. The main purpose of SOSMC is to drive the sliding surface and its derivative to zero. Among the SOSMC methods, twisting (TA), super twisting algorithm (STA), sub-optimal, and quasi-continuous algorithms are the most well-known algorithms [15].

Power electronics converters are variable structure systems due to the on-off operation of the switches. SMC, which is a form of variable structure system, is one of the most suitable methods used in the control of DC/DC converters [16]. Many studies based on conventional SMC have been studied in the literature [17-19]. General design criteria and issues for the sliding mode controller used in the buck converter are presented in [9]. In [20], a buck converter model-based SMC method with bilinear terms was proposed. In [21], a genetic algorithm-based PPE was proposed for a buck converter. The appropriate sliding surface was selected by determining the poles via the genetic algorithm. However, there are problems in the

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conventional SMC method, such as steady-state error, chattering, and output voltage fluctuation. To get better performance from the closed-loop system, a terminal sliding-mode controller has been developed in [22]. But the problem of singularity arises. This problem has been eliminated with the non-singular terminal sliding mode controller designed in [23]. In [24], SOSMC was applied to the linear buck converter to reduce chattering. In recent years [16, 25-30], many different controllers have been proposed to reduce chattering using SOSMC algorithms and to obtain robust performance against external disturbances and parameter uncertainties.

As a result of the literature review, it was seen that many controller designs were made with SOSMC algorithms. But, in these designs, controller designs were made using only one algorithm. The presented controllers are compared with controllers of different structures (PI, PI-SMC, classical SMC, Terminal SMC, Adaptive SMC). Therefore, in this paper, the design of second-order sliding mode control algorithms and their comparison with each other are presented to guide the researchers. Second-order sliding mode controller designs for buck converters are offered using the control algorithm with prescribed convergence law (PCL), twisting algorithm (TA), and super twisting algorithm (STA), which are SOSMC algorithms. The proposed controllers adjust the output voltage of the buck converter according to the desired reference voltage. The performances of the controllers designed separately with these three algorithms were evaluated with simulations in Matlab/Simulink environment. In the simulations, its responses to the change of reference voltage, disturbances in the input voltage, and load were analyzed and dynamic responses were compared. The main contributions of this study are: In the literature, these algorithms are generally compared with conventional SMC techniques or traditional linear control methods (PI, PID…) alone. In this study, three different second-order sliding mode controllers designed with SOSMC algorithms were compared and analyzed under the same conditions and conditions. The reactions and dynamic responses to disturbances in the system are thoroughly investigated. With the proposed controllers, chattering is reduced and robustness is ensured. The design processes are explained step by step.

The rest of this work is organized as follows: The buck converter's dynamic model was obtained and SOSMC was introduced in a brief section II. The designs of controllers based on SOSMC algorithms were presented and the criteria for stability are described in section III. In section IV, the resulting simulations and dynamic responses are presented and discussed. Finally, the results are given in section V.

II. DYNAMIC MODEL OF BUCK CONVERTER

In Fig. 1, which shows a buck converter model, i_L, i_C, i_R, v_o and v_{in} represents the inductor current, capacitor current, load current, output voltage and input voltage respectively and R is load resistance, L is an inductor and C is capacitor. u is the control signal obtained for the switch. To design the controller, the following state-space equations

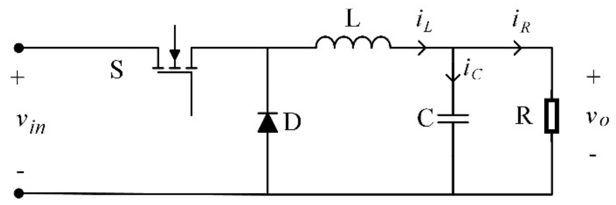

Fig. 1. DC-DC buck converter

of the buck converter are derived based on the switch's on-off states:

Switch "on", ($0 < t < dt$)

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

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

Switch "off", ($dt < t < T$)

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

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

T is the switching period and d is the duty ratio of the buck converter. Using the state-space averaging method, we can obtain the dynamic model of the buck converter [31]:

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

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

SMC is one of the most robust methods for controlling nonlinear systems against parameter uncertainties and disturbances. In SMC, the system state curves are tried to converge in finite time with the discrete-time control rule to a special line defined as the sliding surface [32]. SOSMC is proposed to eliminate the disadvantages of SMC such as the chattering problem, and relative degree restriction. The discontinuous control rule, which acts in the first derivative in classical SMC, is applied in the higher derivatives of the system in SOSMC. So, the real control rule is always continuous and the chattering effect is suppressed [33]. A single-input single-output nonlinear system is as follows:

$$\dot{x} = f(x) + g(x)u \tag{7}$$

$$y = \sigma(x, t) \tag{8}$$

Here x is the state variables of the system, y is the output, u is the control input. $f(x)$, $g(x)$ and $\sigma(x)$ are smooth functions. If the relative degree of the system is one, the classical SMC (or first-order SMC) controller is usually used. Otherwise, it is necessary to design SOSMC. The widely used SOSMC forces both the sliding surface $\sigma(x, t)$ and its derivative $\dot{\sigma}(x,t)$ to converge to zero. In doing so, it uses the discontinuous control rule $\ddot{\sigma}(x, t)$ in the second derivative of the sliding surface [23]. It is used for systems where the TA and PCL output has a relative degree of two relatives to the control input. That is, the control rule must appear in the second derivative of the sliding surface. If the relative order of the system is one, the control rule must be in the first derivative of the sliding surface. STA is also used for such systems [28, 34, 35]. The general definitions for SOSMC are written as:

$$\dot{\sigma} = \frac{\partial}{\partial t}\sigma(x,t) + \frac{\partial}{\partial x}\sigma(x,t)[f(x) + g(x)u] \tag{9}$$

$$\ddot{\sigma} = \frac{\partial}{\partial t}\dot{\sigma}(x,t) + \frac{\partial}{\partial x}\dot{\sigma}(x,t)[f(x) + g(x)u] + \frac{\partial}{\partial u}\dot{\sigma}(x,t)\dot{u} = \theta(x,t) + \gamma(x,t)\dot{u} \tag{10}$$

$$\theta(x,t) = \frac{\partial}{\partial t}\dot{\sigma}(x,t) + \frac{\partial}{\partial x}\dot{\sigma}(x,t)[f(x) + g(x)u] \tag{11}$$

$$\gamma(x,t) = \frac{\partial}{\partial u}\dot{\sigma}(x,t) \tag{12}$$

Through the written equations, chattering is eliminated by employing the derivative of the control input and the sliding surface. It also ensures the system's stability. Different stability conditions are applied for SOSMC algorithms. These requirements will be explained in detail as each controller is designed.

III. Second-Order Sliding Mode Algorithms for Controller Design

To control the output voltage of the buck converter, the sliding surface must first be determined in the controller design. The sliding surface is defined as the error between the output voltage v_o and the reference voltage v_{ref}:

$$\sigma = v_o - v_{ref} \tag{13}$$

Taking the derivative of the sliding surface:

$$\dot{\sigma} = \dot{v}_o - \dot{v}_{ref} \tag{14}$$

$$\ddot{\sigma} = \frac{1}{C}\frac{di_L}{dt} - \frac{1}{RC}\frac{dv_o}{dt} \tag{15}$$

Since the reference voltage is constant, its derivative will be zero, and equation (6) is obtained. The second derivative of the sliding surface:

$$\ddot{\sigma} = \left(\frac{1}{R^2C^2} - \frac{1}{LC}\right)v_o - \frac{1}{RC^2}i_L + \frac{v_{in}}{LC}u \tag{16}$$

According to equations (11) and (12), the equations of the buck converter are written:

$$\theta(x,t) = \left(\frac{1}{R^2C^2} - \frac{1}{LC}\right)v_o - \frac{1}{RC^2}i_L \tag{17}$$

$$\gamma(x,t) = \frac{v_{in}}{LC} \tag{18}$$

Based on equation (10), different SOSMC algorithms are applied to the buck converter. Conditions for controller design can be calculated using equations (17) and (18). Because of the formulas found, the parameters of the controller for PCL, TA, and STA were calculated. Figure 2 illustrates the basic concept of the design work. For each method, the internal design of the controller block is shown individually.

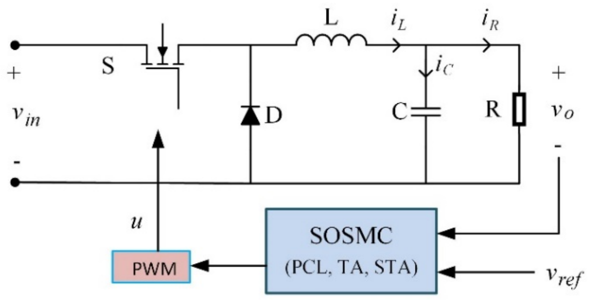

Fig. 2. Controller with SOSMC algorithms for buck converter

A. Prescribed Convergence Law

TA and PCL algorithms are applied for systems with a relative degree of two. In other words, the control rule must appear in the sliding surface's second derivative with regard to time. This is seen in equation (14). Figure 3 depicts the PCL algorithm's structure. The control rule of the PCL algorithm is as follows:

$$u = \frac{1}{2}(1 - \alpha sign(\dot{\sigma} + \beta|\sigma|^{0.5} sign(\sigma))) \tag{19}$$

The system is modeled by inserting the parameters from Fig. 3 into the SOSMC block in Fig. 2. α, β *and* Z in equations (19) and (20) are greater than zero, and the criteria in equationa (20-22) should be considered for stability:

$$0 < \Gamma_m < \gamma(x,t) < \Gamma_M \tag{20}$$

$$|\theta(x,t)| \leq Z \tag{21}$$

$$\alpha\Gamma_m - Z > \frac{\beta^2}{2} \tag{22}$$

Stability is ensured by determining the limits of the PCL algorithm. Since the sliding surface is determined as the output voltage error, the limits from Eqs. (17 and 18) are as follows:

$$0 < \frac{v_{in\_min}}{LC} < \gamma(x,t) < \frac{v_{in\_max}}{LC} \tag{23}$$

$$|\theta| \leq \left|\frac{1}{LC}v_{o\_max} + \frac{1}{R_{min}C^2}\left(\left(\frac{v_{ref}}{R} + 0.2\right) - \frac{v_{o\_min}}{R_{min}}\right| \tag{24}$$

The tolerance at the output voltage is around 0.01 V and the inductor current is around 0.2 A. Also, the inductor current at steady state is $i_L = \frac{v_{ref}}{R}$. The coefficients are determined using Eq. (22) as follows:

$$\alpha\frac{v_{in\_min}}{LC} - \left(\frac{1}{LC}v_{o\_max} + \frac{1}{R_{min}C^2}\left(\left(\frac{v_{ref}}{R} + 0.2\right) - \frac{v_{o\_min}}{R_{min}}\right)\right) > \frac{\beta^2}{2} \tag{25}$$

If the inequality in Eq. (25) is satisfied, the PCL algorithm's closed-loop system stability is ensured.

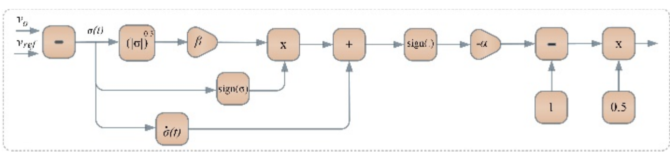

Fig. 3. PCL algorithm

B. Twisting Algorithm

Figure 4 illustrates the twisting algorithm's structure (TA). The TA control rule is written as:

$$u = -\alpha\, sign(\sigma) + \beta sign(\dot{\sigma}) \tag{26}$$

The general conditions in equation (20) are valid for this algorithm. It must also meet the following conditions.

$$\alpha > \beta \text{ and } \frac{Z}{\Gamma_m} < \beta \tag{27}$$

$$(\alpha + \beta)\Gamma_m - Z > (\alpha - \beta)\Gamma_M + Z \tag{28}$$

Because the relative degree is two, Eqs (20 and 21) also apply to the twisting algorithm. Equations (17 and 18) should be substituted in Eq. (27) to determine the coefficients.

$$\frac{\left|\frac{1}{LC}v_{o\_max}+\frac{1}{R_{min}C^2}\left(\left(\frac{v_{ref}}{R}+0.2\right)-\frac{v_{o\_min}}{R_{min}}\right|}{\frac{v_{in\_min}}{LC}} < \beta \tag{29}$$

α can be found by substituting other parameters in Eq. (28). The sliding surface converges asymptotically in finite time when the above convergence requirements are fulfilled. As a result, the closed-loop system's stability is assured.

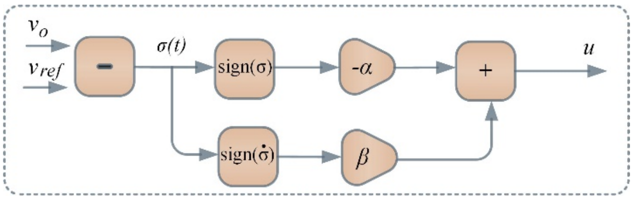

Fig. 4. Twisting algorithm

C. Super Twisting Algorithm

The STA method, in contrast to the previous two algorithms, is used for systems having a relative degree of one. The surface chosen in the prior algorithms has a relative degree of two. Therefore, several different operations should be performed while determining the surface. The operations will be redefined over the output voltage error (e) so that the sliding surface is the first derivative of the control input u. If set to $v_o - v_{ref} = e$ the sliding surface is as follows [36]:

$$\sigma = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \tag{30}$$

$$e = v_o - v_{ref} \tag{31}$$

$$\dot{e} = \dot{v}_o = \frac{i_L}{C} - \frac{v_o}{RC} \tag{32}$$

$$\ddot{e} = \frac{1}{C}\frac{di_L}{dt} - \frac{1}{RC}\frac{dv_o}{dt} = \left(\frac{1}{R^2C^2} - \frac{1}{LC}\right) v_o - \frac{1}{RC^2} i_L + \frac{v_{in}}{LC} u \tag{33}$$

$$\dddot{e} = i_L\left(\frac{1}{R^2C^2} - \frac{1}{LC^2}\right) + v_o\left(\frac{2}{LRC^2} - \frac{1}{R^3C^3}\right) - \left(\frac{V_{in}}{LRC^2}u + \frac{V_{in}}{LC}\dot{u}\right) \tag{34}$$

$$\sigma = \dot{e} + \lambda e \tag{35}$$

$$\dot{\sigma} = \ddot{e} + \lambda \dot{e} \tag{36}$$

When the expressions in Eq. (36) are written instead, it is seen that the control signal u comes. To calculate the parameters in the STA algorithm, the second derivative of the sliding surface is taken as follows:

$$\ddot{\sigma} = \dddot{e} + \lambda \ddot{e} = \theta(x,t) + \gamma(x,t)\dot{u} \tag{37}$$

Provided that the rules in Eqs. (20 and 21) are provided, the conditions specified in Eq. (38) must be met to achieve convergence in finite time [29, 37].

$$\beta > \frac{C}{\Gamma_m}, \quad \alpha^2 \geq \frac{2(\Gamma_m\beta + C)^2\Gamma_M{}^2}{\Gamma_m{}^4(\Gamma_m\beta - C)} \tag{38}$$

The STA design scheme is depicted in Fig. 5. The STA control rule is as follows:

$$u_a = -\alpha|\sigma|^{0.5} sign(\sigma)$$

$$\dot{u}_b = -\beta sign(\sigma) \tag{39}$$

$$u_{sta} = u_a + u_b$$

The suggested controller's stability analysis has been demonstrated. u_b is calculated by integrating from (34). The Lyapunov function is as follows:

$$V(x) = 2\beta\sigma + \frac{1}{2}u_b{}^2 + \frac{1}{2}(\alpha|\sigma|^{0.5}sign(\sigma) - u_b)^2 \tag{40}$$

The quadratic version of the Lyapunov function is as follows:

$$V(x) = \zeta^T P \zeta \tag{41}$$

$$V(x)|\sigma|^{0.5}sign(\sigma), \omega]\begin{bmatrix} 2p + \frac{1}{2}\alpha^2 & -\frac{1}{2}\alpha \\ -\frac{1}{2}\alpha & 1 \end{bmatrix}\begin{bmatrix} |\sigma|^{0.5}sign(\sigma) \\ u_b \end{bmatrix} \tag{42}$$

$V(x)$ is a positive definite. Using the derivative of $V(x)$:

$$\dot{V} = \dot{\zeta}^T P\zeta + \zeta^T P\dot{\zeta} = -\frac{1}{|\sigma|^{0.5}}\zeta^T Q \zeta \tag{43}$$

$$Q = \begin{bmatrix} \alpha\beta + \alpha^3 & -\alpha \\ -\frac{1}{2}\alpha^2 & \frac{1}{2}\alpha \end{bmatrix} \tag{44}$$

Q>0 and $\dot{V}$<0 ensures the stability of the system according to the Lyapunov's stability theory [38].

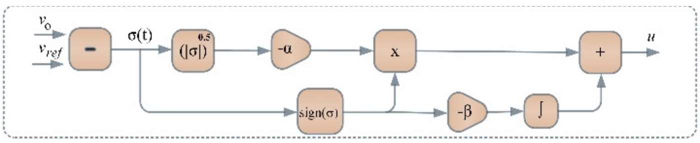

Fig. 5. Super twisting algorithm

IV. Simulations Results

The performance of the designed controllers was tested in Matlab/Simulink environment under different conditions. Controllers for three different situations were compared with each other and discussed. Table I shows the parameters used in the simulations and their values. When there is no controller in the system, the output voltage works unstable and extremely oscillating. To regulate the output voltage of the buck converter, the design of the second-order sliding mode controller was designed with different algorithms. To control the output voltage in the best way, the coefficients in each algorithm were determined by optimizing. The coefficients of the algorithms are given in Table II. Figure 6 shows the controllers' initial reaction to each method. With an oscillation of about 0.1 V, the TA settles to the reference. PCL and STA followed the reference at an error of less than 0.1 V. Overshoot and oscillation occur in TA and STA. In PCL, on the other hand, almost no overshoot occurs. TA and STA access the reference faster than PCL. After steady-state, the steady-state error is very high for TA compared to others. Input voltage increased from 24 V to 60 V in 0.5 ms. As seen in Fig. 6, the STA algorithm gives the best response to the disorder. After the change, the chattering of the TA and PCL increases even more.

TABLE I. SIMULATION PARAMATERS

Parameters	Values
Input voltage (v_{in})	20 V-24 V
Reference voltage (v_{ref})	12 V
Switching frequency (f_s)	10 kHz
Inductor (L)	150 µH
Capacitor (C)	20 µF
Load (R)	1-10 Ω

TABLE II. PARAMATERS OF SOSMC ALGORTIHMS

Parameters	TA	STA	PCL
α	9	30	1
β	0.1	5	9000
λ	-	1	-

After the controllers stabilized the output voltage, the input voltage was kept constant and the output load was increased from 1Ω to 10Ω in 0.5 ms. The reaction of the controllers to this disorder is shown in Fig. 7. PCL exhibited less chattering in the presence of load disturbance. After the load change in TA, chattering and oscillation increased even more. Chattering and oscillation in the STA increased compared to the state before the change, but less than in TA. After the output voltage stabilizes with the STA, the chattering gradually decreases. Since the errors obtained in these three algorithms are quite small, robust results have been obtained against load disturbance.

The controllers follow the output according to the desired reference voltage. About 1 ms. when the reference voltage is increased from 12 V to 18 V in Fig. 8. It is seen that it regulates the output voltage in as short a time as possible. It is seen that the three algorithms used give a fast dynamic response. Chattering has increased slightly compared to the situation before the change, but this is a very minor deterioration.

The dynamic responses of the above simulations are given below in tables. Table III's first section depicts the changes that occur when there is no change or disorder (v_{in}=24 V-v_{ref}=12 V-R=1 Ω). According to these values, the PCL algorithm gave the best settling time and the least overshoot. TA has the best rise time, while STA has fewer errors. In the second part, when the input voltage changes (v_{in}=60 V, v_{ref}=12 V, R=1 Ω), the STA responds with less error and the best rise time compared to the others. PCL has

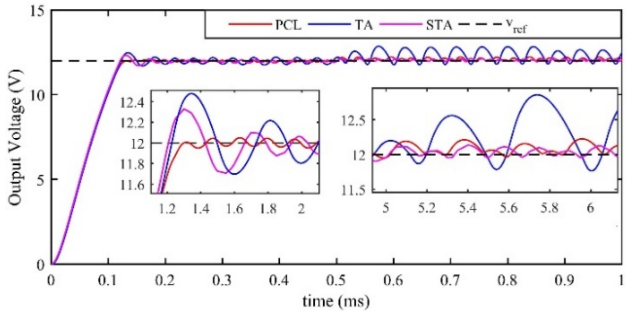

Fig. 6. The output voltage response when input voltage (v_{in}) changes from 24 V to 60 V

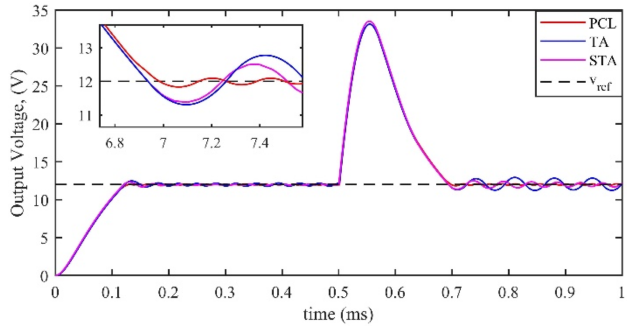

Fig. 7. The output output voltage response when load resistance (R) changes from 1 Ω to 10 Ω

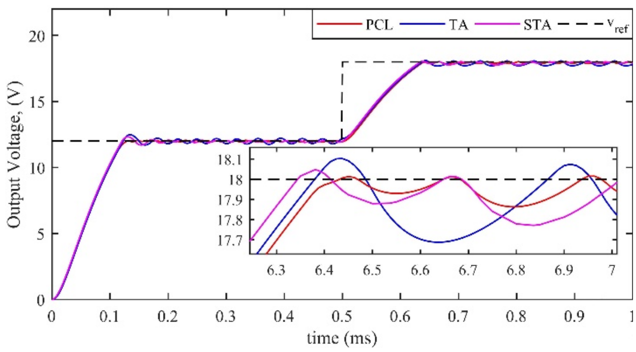

Fig. 8. The output output voltage response when the reference voltage changes from 12 V to 18 V

the least overshoot and settling time, while TA has the worst dynamic response.

In the first part of Table IV (v_{in}=24 V, v_{ref}=12 V, R=10 Ω) it is seen that the PCL algorithm provides the best settling time when the load value is increased. STA provides the least overshoot. TA algorithm provides the best response for rising time and steady-state error. When the reference voltage is changed in the second part (v_{in}=24 V, v_{ref}=18 V, R=1 Ω), the rise and settling times are almost the same for all algorithms.

However, STA gave the best dynamic response for overshoot and error. In all simulations, it was concluded that the controllers showed superior properties at different points. To control the output voltage of the buck converter, the important conditions should be determined and a controller with the appropriate algorithm should be selected. It is seen from the tables and figures that all algorithms show fast and robust dynamic responses for each situation. The differences in the dynamic response of the controllers to the changes and disturbances that occur are extremely small. As a result, all proposed algorithms regulate the buck converter's output voltage stably and robustly.

V. CONCLUSION

In this paper, a second-order sliding mode controller with prescribed convergence law, twisting algorithm, and the super twisting algorithm is proposed for the DC/DC power converter. The SOSMC method and the necessary conditions are briefly mentioned for each algorithm. The designed controllers have been tested in Matlab/Simulink environment and their accuracy has been proven. The dynamic responses of the controllers under different conditions are shown in the figures by varying the input voltage, load resistance and reference voltage of the system. Dynamic responses are presented in tables. The simulations and controllers were compared and their superiority over each other was analyzed. Controllers are discussed, highlighting the better points of each algorithm. It has been demonstrated that it provides robust dynamic responses in the presence of load resistance and input voltage disturbances. It is presented that the proposed controllers reduce the steady-state error and settling time

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TABLE III. DYNAMIC RESPONSES FOR START-UP AND INPUT VOLTAGE VARIATION

simulations	v_{in}=24 V-v_{ref}=12 V-R=1 Ω			v_{in}=60 V-v_{ref}=12 V-R=1 Ω		
algorithm	TA	STA	PCL	TA	STA	PCL
settling time (ms)	0.19	0.155	**0.12**	0.31	0.157	**0.124**
rise time (ms)	**0.0863**	0.0869	0.0873	0.0925	**0.0863**	0.0878
overshoot (%)	5.26	2.84	**0.85**	3.04	3.15	**1.03**
steady state error (%)	0.14	**0.01**	0.04	0.48	**0.045**	0.1

TABLE IV. DYNAMIC RESPONSES FOR THE LOAD DISTURBANCE AND REFERENCE VOLTAGE VARIATION

simulations	v_{in}=24 V-v_{ref}=12 V-R=10 Ω			v_{in}=24 V-v_{ref}=18 V-R=1 Ω		
algorithm	TA	STA	PCL	TA	STA	PCL
settling time (ms)	0.99	0.98	**0.69**	0.062	0.062	0.062
rise time (ms)	**0.084**	0.088	0.086	0.058	0.056	0.056
overshoot (%)	174.59	**169.13**	178.25	1.64	**0.47**	0.67
steady state error (%)	**0.03**	0.18	0.08	0.19	**0.03**	0.09

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