Performance of the adaptive sliding mode control scheme for output voltage control of the DC/DC buck converter system

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Abstract. In this work, the DC output voltage of a step-down DC/DC buck converter system has been controlled using different schemes of sliding mode controllers (SMCs) such as classical sliding mode controller (CSMC), modified sliding mode controller (MSMC) and the adaptive sliding mode controller (ASMC). As the DC/DC buck converter is a nonlinear and time-variant system, the application of linear control techniques for controlling this type of converters is not always suitable. Therefore, the SMCs are used here due to their characteristic features of maintaining the overall system stability with acceptable performance in the absence or presence of the parameters uncertainty and external disturbance. The simulation results obtained using MATLAB/Simulink software show the advantages of using ASMC in terms of reducing the settling time, the chattering value in the control action and the steady state error but the hitting time is increased when compared with the CSMC. Besides, the simulation results show the advantages of using ASMC in terms of reducing the settling time and the chattering value, but the steady state error and the hitting time are increased when compared with the MSMC. Since the buck converter is a fast response system, the performance of the ASMC is better than that of the CSMC and MSMC in terms of reducing the settling time and the chattering value in the control action.

Keywords: DC/DC Converters, Buck Converter, Classical Sliding Mode Controller (CSMC), Modified Sliding Mode Controller (MSMC), Adaptive Sliding Mode Controller (ASMC).

1. Introduction

Power electronic converters are used in almost every field of modern control system due to their attractive features such as flexibility in control, low cost, and high efficiency. The DC/DC converters convert DC voltage level to another level such as buck converter, boost converter and buck-Boost converter. The DC/DC buck converters are powerful electronic devices that are used in devices where the output voltage is less than the input voltage and these types of converters have a wide range of functionality in widespread applications such as computer systems, portable devices, office equipment, etc. Because of the switching operation of buck converters, they are considered as a nonlinear and a time-varying system [1, 2].

In the DC/DC buck converters, it is always required to achieve a constant output voltage in spite of changes in the input source voltage, the load current, and variations in the buck converter system elements values. Therefore, different control methodologies have been proposed to ensure stability as well as fast transient response such as adaptive hysteresis controllers [3], observer controller [4], sliding model controller [2], PWM with dead time controller-based FPGA [5], Modified Elman Neural-PID Controller [6], direct pole placement controller [7], adaptive backstepping control using chebyshev neural network [8], model predictive controller [9], and Fuzzy-PID controller [10].

The motivation of this paper is to achieve reducing the variation in the output voltage despite changes in the load current ,input source voltage, and variations in element values of the buck
converter circuit that affect the portable devices working. To handle these issues in the transient and steady state responses in the closed loop system, different schemes of sliding mode controllers are proposed in this paper.

The main contributions of this paper are listed as follows:

- Different SMCs techniques are applied to regulate the output voltage of the buck converter circuit.
- Investigating the performance robustness of the different SMCs by changing the load resistance value of the buck converter circuit as a parameter uncertainty problem.

The remainder of this paper is organized in the following manner: Section 2 contains the mathematical model of the buck converter circuit. Section 3 explains in detail the design of different SMCs schemes. The numerical simulation results and discussion for the different SMCs schemes are presented in section 4. Finally, the conclusions are explained in section 5.

2. Buck Converter Circuit Model

A DC/DC buck converter can be classified as a type of attenuation or chopper circuits with an output voltage less than its input voltage, so it is known as step down converter. The basic topology of the buck converter that is operating in the continuous conduction mode (CCM) is shown in Figure 1 [11].

![Figure 1. The buck convertor model.](image-url)

This type of buck converter has a diode and MOSFET as a switching element and the converter uses one inductor and one capacitor as energy storing elements. In CCM, the buck converter operates in two switching modes as follows [11-13]:

(a) When switch Q is ON and diode D is OFF for time $0 < t < ZT$:

At this period, the diode is in reverse biased and in this case, the inductor current and the output voltage equations are given by equations (1) and (2) respectively as follows:

$$\frac{di_L}{dt} = \frac{1}{L} (E - V_o)$$

$$\frac{dv_o}{dt} = \frac{1}{c} (i_L - \frac{v_o}{R})$$

Where $E$ is the input voltage; $i_L$ is the inductor current; $V_o$ is the buck circuit output voltage; $R$ is the load resistor; $C$ is the buck circuit capacitor; $L$ is the buck circuit inductance; and $Z$ is the duty cycle.

(b) When switch Q is OFF and diode D is ON for time $ZT < t < T$:

At this period, the diode is in forward biased because of the polarity of the inductor changes. In this case, the inductor current and the output voltage equations are given by equations (3) and (4) respectively as follows:

$$\frac{di_L}{dt} = -\frac{v_o}{L}$$

$$\frac{dv_o}{dt} = \frac{1}{c} (i_L - \frac{v_o}{R})$$
The equations (1), (2), (3), and (4) can be combined with ON and OFF switching control $\nu$ as follows:

$$\frac{di}{dt} = \frac{1}{L} (\nu E - V_o)$$  \hspace{1cm} (5)$$

$$\frac{dv_o}{dt} = \frac{1}{C} (i_L - \frac{V_o}{R})$$  \hspace{1cm} (6)$$

Where $\nu$ is the switching function and takes 0 and 1 for the switch state OFF and ON, respectively. This switching function is determined by using SMCs, which will be designed later.

The error of the output voltage ($x_1$) and its time derivative ($x_2$) are defined by equations (7) and (8) respectively as follows:

$$x_1 = V_o - V_d$$  \hspace{1cm} (7)$$

$$x_2 = \dot{x}_1 = \frac{dV_o}{dt}$$  \hspace{1cm} (8)$$

Finally, the error of the output voltage ($x_1$) and its time derivative ($x_2$) are represented as the state variables of the buck converter system. Therefore, the final state equations of the system are described as in equations (9) and (10) as follows:

$$\dot{x}_1 = x_2$$  \hspace{1cm} (9)$$

$$\dot{x}_2 = -\frac{x_1}{LC} - \frac{x_2}{RC} + \frac{1}{LC} (\nu E - V_d)$$  \hspace{1cm} (10)$$

### 3. Sliding Mode Controllers Design

The SMC can be considered as a type of nonlinear and robust controllers and is classified as a special case of Variable Structure Controller (VSC) that is described as a system whose physical structure is changed intentionally during the time by a predetermined structure control law. This type of controllers can handle linear and nonlinear systems in the presence or absence of the variance in their parameters and the external disturbances [14].

The SMC is a discontinuous feedback control that forces the states of the system to reach and remain on a specific surface within the state space (called sliding surface) [15]. The sliding surface can be described in equation (11) as follows:

$$s = \dot{e} + \lambda e$$  \hspace{1cm} (11)$$

Where $\lambda$ is the sliding slope coefficient, which is greater than zero, $e$ is the output voltage error, and $\dot{e}$ is the time derivative of the output voltage error.

In this type of controllers, the control law is composed of two parts as follows [15]:

$$\nu \nu = \nu_{eq} + \nu_{dis}$$  \hspace{1cm} (12)$$

Where, $\nu_{eq}$ represents the equivalent control law and $\nu_{dis}$ represents the discontinuous control law.

The equivalent control law is responsible for orientation the state trajectory of the system toward sliding surface ($s = 0$) while the discontinuous control law is needed to keep the system state trajectory to move always towards the sliding surface [14, 15]. The CSMC suffers from a chattering problem that is considered as a major drawback in this type of controllers [15].

This chattering problem is described by the states repeatedly crossing rather than remaining on the sliding surface and this due to the $\text{sign}(s)$ function in the discontinuous control action as shown in equation (13) [15].

$$\nu_{dis} = -k(t) \text{sign}(s)$$  \hspace{1cm} (13)$$
Where, \( k(t) \) represents the discontinuous gain and \( \text{sign}(s) \) represents a signum function that is defined by equation (14):

\[
\text{sign}(s) = \begin{cases} 
1, & s > 0 \\
-1, & s < 0 \\
0, & s = 0 
\end{cases}
\]

(14)

Several methods were proposed to attenuate the chattering phenomenon, some of them like using the saturation function rather than the sign discontinuous function in order to modify the discontinuous control law [15]. Thus, instead of forcing the states to lie on the sliding surface they are forced to remain within a small boundary layer about the surface [14, 15]. Therefore, the control law for the MSMC is written as follows:

\[
v\nu = v_{eq} - k(t)\text{sat}(s)
\]

(15)

The \( \text{sat}(s) \) function is defined by equation (16) as follows:

\[
\text{sat}(s) = \begin{cases} 
+1, & s \geq \varphi \\
\frac{s}{\varphi}, & -\varphi < s < \varphi \\
-1, & s \leq -\varphi 
\end{cases}
\]

(16)

Adaptive control is defined as a controller that has the ability to adjust its behaviour in response to change in the process dynamics and the character disruptions [16]. The ASMC is consisting of the adaptive control method and SMC methodology. Finally, the ASMC is also utilized in order to improve chattering reduction and the control law for this controller is written as in equation (17) [17].

\[
v\nu = v_{eq} - k(t)\text{sat}(s)
\]

(17)

Let \( \epsilon \) be a small positive number, then \( k(t) \) is calculated according to the equations (18) and (19). Set the initial value of \( \mu \) as \( \mu_{\text{initial}} = k \), then:

\[
\dot{\mu} = \sigma |s(x,t)|, \text{sign}(|s(x,t)|) - \epsilon)
\]

(18)

Then the value of \( k(t) \) is choosing according to the equation (18) as follows:

\[
k(t) = \begin{cases} 
\mu, & k_{\text{min}} < \mu < k_{\text{max}} \\
k_{\text{min}}, & \mu \leq k_{\text{min}} \\
k_{\text{max}}, & \mu \geq k_{\text{max}}
\end{cases}
\]

(19)

Where the initial value is chosen as follows:
\( \sigma > 0, \epsilon > 0, k_{\text{min}} < k(0) < k_{\text{max}}, k_{\text{min}} \) represents the minimum value of \( k(t) \) and \( k_{\text{max}} \) represents the maximum value of \( k(t) \).

4. Simulation Results and Discussion
In this section, different types of SMCs for controlling the output voltage of the DC/DC buck converter circuit are simulated using MATLAB / SIMULINK package. The buck converter circuit components values are taken from Table 1 [2].
Table 1. The buck converter model components’ values [2].

| Component and Symbol                  | Value and Unit |
|---------------------------------------|----------------|
| The Inductance of The Converter (L)   | 4.5 mH         |
| The Capacitor of The Converter (C)    | 47 μF          |
| The Load Resistance of The Converter (R) | 7 Ω          |
| Input Voltage (E)                     | 20 V           |
| Switching frequency (Fs)              | 100 kHz        |
| Duty Ratio (Z)                        | 48 %           |

The proposed SIMULINK block diagram of different types of SMCs for controlling the buck converter output voltage is shown in Figure 2 and the simulation results take into consideration the uncertainty problem. The uncertainty problem means that the load resistance of the circuit is decreased suddenly by 50% from its nominal value at the moment \( t = 5 - 6 \) sec and then it is returned to its nominal value.

Figure 2. The SIMULINK block diagram of the controlled system.

The simulation results for each type of SMC with the initial conditions as \( x_1 = 1 \) V and \( x_2 = 0 \) V with the desired output voltages as 10 V are described as follows:

4.1. Simulation results using CSMC

The output voltage error and its time derivative are approximately reached zero value in steady state of the desired output voltage as shown in Figures 3 and 4, respectively. This means that the system is asymptotically stable.
The voltage tracking results for the buck converter system controlled by CSMC reveals that the settling time equals 0.75 Sec and the response of the buck system has a $3 \times 10^{-4}$ V steady state error as shown in figures 5 a, b, and c.

![Figure 3](image3.png) **Figure 3.** The error vs. time in CSMC.

![Figure 4](image4.png) **Figure 4.** The time derivative of error vs. time in CSMC.

The voltage control action ($v$) of the CSMC with the $\text{sign}$ function has a chattering problem and the value of the chattering equals $4 \times 10^{-2}$ V as shown in Figures 6 a and b.

![Figure 5](image5.png) **Figure 5.** (a) The output voltage of the buck converter system using CSMC, (b) The load resistance variation and steady state error in output voltage response using CSMC, and (c) The settling time in output voltage response using CSMC.

![Figure 6](image6.png) **Figure 6.** (a) The voltage control action using CSMC and (b) The chattering problem in Voltage control action using CSMC.
The CSMC that uses a *sign* function makes the state trajectory hit the sliding surface vertically and causing a chattering phenomenon as illustrated in Figure 7.

![Figure 7](image-url)

**Figure 7.** The phase plane between $x_1$ and $x_2$ in CSMC.

The hitting time can be described as the required time for the states to hit the sliding surface and equals $5.6 \times 10^{-6}$ Sec in the CSMC as depicted in Figures 8 a and b.

(a)  
(b)

![Figure 8](image-url)

**Figure 8.** (a) The sliding surface vs. time in CSMC and (b) The hitting time using CSMC.

4.2. Simulation results using MSMC

The system is asymptotically stable because the output voltage error and its time derivative are approximately reached zero value in the steady state at the desired output voltage as shown in Figures 9 and 10, respectively.

![Figure 9](image-url)

**Figure 9.** The error vs. time in MSMC.

![Figure 10](image-url)

**Figure 10.** The time derivative of error vs. time in MSMC.
The voltage tracking results of the buck converter system controlled by MSMC shows that the output voltage response has a settling time equals 0.70 Sec and a $5 \times 10^{-9} \, V$ steady state error as shown in Figures 11 a, b, and c.

![Figure 11](image1.png)

**Figure 11.** (a) The output voltage of the buck converter system using MSMC, (b) The load resistance variation and steady state error in output voltage response using MSMC, and (c) The settling time in output voltage response using MSMC.

The chattering problem in the voltage control action $(\nu \nu)$ of the MSMC using $sat$ function was reduced to $1.92 \times 10^{-4} \, V$ in comparison with the CSMC as shown in Figure 12 a and b.

![Figure 12](image2.png)
Figure 12. (a) The voltage control action using MSMC and (b) The chattering problem in Voltage control action using MSMC.

The MSMC that uses a $sat$ function makes the state trajectory hit the sliding surface in an arc shape and thus, the chattering problem is reduced as illustrated in Figure 13.

![Figure 13](image)

**Figure 13.** The phase plane between $x_1$ and $x_2$ in MSMC.

The hitting time in the MSMC equals $10 \times 10^{-6}$ Sec as depicted in Figures 14 a and b.

(a)

![Figure 14a](image)

(b)

![Figure 14b](image)

**Figure 14.** (a) The sliding surface vs. time in MSMC and (b) The hitting time using MSMC.

4.3. Simulation results using ASMC

The system is also asymptotically stable because the output voltage error and its time derivative in steady state are approximately reached zero value at the desired output voltage as shown in Figures 15 and 16, respectively.

(a)

![Figure 15](image)

(b)

![Figure 16](image)

**Figure 15.** The error vs. time in ASMC.  **Figure 16.** The time derivative of error vs.
The voltage tracking results of the buck converter system controlled by ASMC shows that the output voltage response has a settling time equals 0.60 Sec and a $6 \times 10^{-6}$ V steady state error as shown in Figures 17 a, b, and c.

**Figure 17.** (a) The output voltage of the buck converter system using ASMC, (b) The load resistance variation and steady state error in output voltage response using ASMC, and (c) The settling time in output voltage response using ASMC.

The chattering problem in the voltage control action ($\nu$) of the ASMC using $sat$ function was reduced again $3 \times 10^{-6}$ V in comparison with the CSMC and MSMC as shown in Figures 18 a and b.

**Figure 18.** (a) The voltage control action using ASMC and (b) The chattering problem in Voltage control action using ASMC.
The ASMC that uses a $sat$ function makes the state trajectory hit the sliding surface in an arc shape and thus, the chattering problem is reduced as illustrated in Figure 19.

![Figure 19. The phase plane between $x_1$ and $x_2$ in ASMC.](image)

The hitting time in the ASMC equals $17 \times 10^{-3}$ Sec as depicted in Figures 20a and b.

![Figure 20. (a) The sliding surface vs. time in ASMC and (b) The hitting time using ASMC.](image)

Finally, the simulation results for these different SMCs are summarized in Table 2. This table reveals that the performance of the ASMC is better than that of the CSMC in terms of reducing the settling time, chattering value in the control action and the steady state error but the hitting time is increased. Similarly, this table reveals that the performance of the ASMC is better than that of the MSMC in terms of reducing the settling time and the chattering value in the control action, but the hitting time and the steady state error are increased.

| Controller Type | $\lambda$ | Settling Time | Hitting Time | Chattering Value | Steady State Error |
|-----------------|-----------|---------------|--------------|------------------|-------------------|
| CSMC 10         | 0.75 Sec  | $5.6 \times 10^{-6}$ Sec | $4 \times 10^{-2}$ V | $3 \times 10^{-4}$ V |
| MSMC 10         | 0.70 Sec  | $10 \times 10^{-6}$ Sec | $1.92 \times 10^{-4}$ V | $5 \times 10^{-9}$ V |
| ASMC 10         | 0.60 Sec  | $17 \times 10^{-3}$ Sec | $2 \times 10^{-6}$ V | $6 \times 10^{-9}$ V |

5. Conclusions

The MATLAB simulation results obtained using different SMCs schemes have been demonstrated for the buck converter circuit in this work. The proposed SMCs schemes have excellent tracking of the desired output voltage with the minimum voltage tracking error and they have also high robustness...
performance that obtained by changing the load resistance value of the buck converter circuit as a parameter uncertainty problem. The performance of the ASMC is better than that of the CSMC in terms of reducing the settling time, chattering value and the steady state error but the hitting time is increased. Besides, the performance of the ASMC is better than that of the MSMC in terms of reducing the settling time and the chattering value but the steady state error and the hitting time are increased. The settling time and the chattering value are the most influential parameters for controlling such a fast response system. Therefore, the performance of the ASMC is better than that of the CSMC and MSMC for controlling the output voltage of the buck converter circuit.

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