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Performance analysis of different methods for optimal sliding mode control of DC/DC buck converter

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ABSTRACT

Performance is always need to be considered in designing DC/DC buck converter. Despite the drastic use of DC/DC buck converter in industry, limitations due to unregulated voltage and current still persist. The dynamic performance of three methods of sliding mode control (SMC) were investigated. The comparative assessment of integral sliding mode control (ISMC) method, showed that the ISMC has an outstanding performance over the other tested methods of two variables with conventional SMC. The excellent performance of ISMC, under diverse operating conditions that include varying input voltage and load resistance, is achievable and it can provide a considerable edge over other control techniques in various field of industries, include electrical vehicle. The ISMC is highly preferable to overcome the problem of varying switching frequency, as well as optimizing power on transient response. The performance characteristic of ISMC shows fast dynamic response of various applications. Detailed simulations of the three SMC methods were carried out to validate the control algorithms using MATLAB/Simulink software.

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1. INTRODUCTION

Buck converter has an essential role in powering electrical and electronic circuits. Though, an important concern regarding stability, regulation of voltage, and current always needs to be addressed. Due to the non-linear behavior of the components of disturb buck converter, such as capacitor and inductor, circuit control plays vital role in converter dynamic performance [1]–[5]. In order to adhere to its intrinsic nonlinearity during abrupt load and input voltage changes as well as ensuring stability with rapid transient response, the DC/DC converters should be designed to work with a relevant control method [6]–[8]. One of the most relevant ways to control converter disturbance is via utilization of sliding mode control (SMC) which is well known by simplicity, stability, and robustness [9]–[15]. The non-linearity of SMC force the dynamics behavior of a non-linear systems to slide in the implementation of a control action that inherent the variable structure of DC/DC converter. The instantaneous values of the state variables reflect the functionality of the converter switches, making trajectory of the system in a proper selected surface called the sliding surface [14], [16]–[19].

Numerous studies propose various methods to design and implement SMC. According to Komurcugil *et al.* [20] an indirect SMC for single-ended primary-inductor converters (SEPIC) was implemented by applying a function of a sliding surface according to the error of input current only. A sliding surface function simplifies and reduces the cost of implementation. A proportional-integral (PI) regulator was used to generate the input current reference. A laboratory prototype of SMC buck and boost converters were used to investigate the validity of the proposed method. The investigation was carried out with simulation to verify the regulation of output voltage regulation during a sudden variation of the input voltage and load resistance as well. Research by Qaisi *et al.* [21] an investigation of a DC/DC buck converter with the SMC by a frequency response method, was implemented. The MATLAB program was used to obtain the graphic presentation of root locus, Polar, Nyquist, and bode plots to assess the performance of the controller of pulse width modulation (PWM) with proportional integral-derivative sliding mode voltage controller (PID SMVC). The controller was designed to obtain the appropriate control parameters and the result showed that the dynamic response of the PID SMVC is fast and efficient for different variety of applications. Research by Das *et al.* [22] an algorithm of integral sliding mode control (ISMC) was implemented for closed loop control of a DC-DC buck converter. The ISMC aimed to tackle the variable switching frequency issue, using PWM scheme using MATLAB/Simulink. The result of the comparative assessment of the ISMC indicate that, with different operating conditions, the frequency has very little fluctuation. According to Nhan *et al.* [23] a SMC method was adopted to manage the position and speed of a slotless self-bearing motor. The simplicity and effectiveness in reaching the reference value was evaluated analytically by using MATLAB/Simulink software. According to Ningappa *et al.* [24] a chattering was suppressed and steady state error was reduced with fast speed in a step down converter by implementing robust reaching law for SMC.

This paper is organized as follow: section 1 included the introduction. Hereinafter, section 2 illustrate the state space modeling and mathematical formula of DC/DC buck converter with CSMC methodology. Also the design of the ISMC and system modeling is included. Section 3 present the simulation outcomes and brief discussion. Finally, in section 4, the conclusions are drawn.

2. TOPOLOGIES AND MODES OF OPERATION

The basic structure of the DC/DC converter is illustrated in Figure 1(a). The state space method for Figures 1(b) and (c) is represented in (1) and (2):

$$\dot{X}_1 = -\frac{1}{L}X_2 + \frac{D}{L}V_o \tag{1}$$

$$\dot{X}_2 = \frac{1}{C}X_1 + \frac{1}{RC}X_2 \tag{2}$$

where X_1 is the inductor current and X_2 is the capacitor voltage.

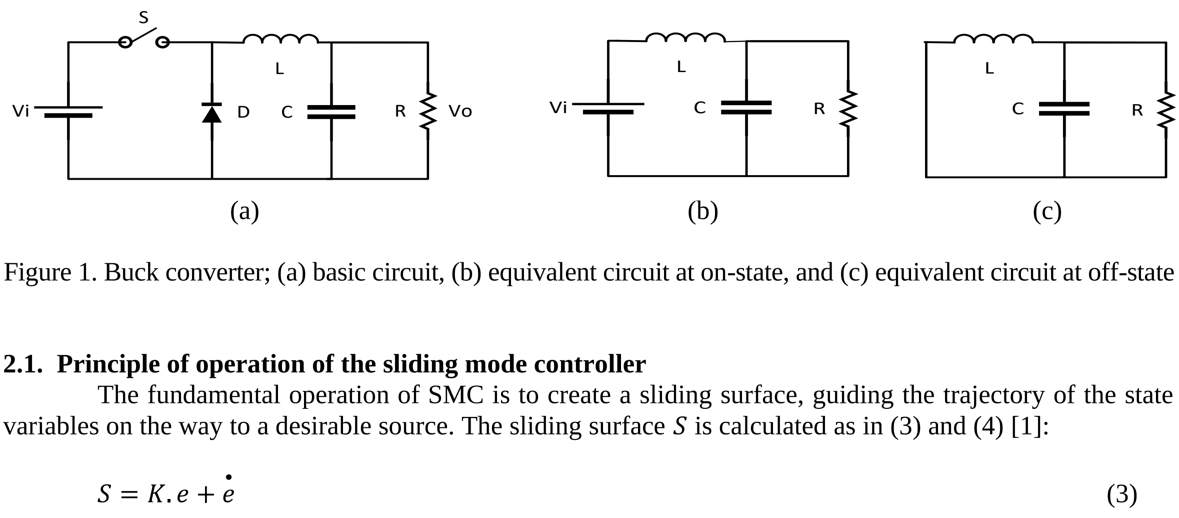


Figure 1. Buck converter; (a) basic circuit, (b) equivalent circuit at on-state, and (c) equivalent circuit at off-state

2.1. Principle of operation of the sliding mode controller

The fundamental operation of SMC is to create a sliding surface, guiding the trajectory of the state variables on the way to a desirable source. The sliding surface S is calculated as in (3) and (4) [1]:

$$S = K.e + \dot{e} \tag{3}$$

$$\lim_{S\to 0} S.\dot{S} < 0 \tag{4}$$

where K is the coefficients of a sliding surface.

2.2. Types of slide mode of operation

In this paper, beside type I: the conventional PWM, there are three types of SMC to be tested. These modes will be examined and discussed based on the number of state variables. Type II: SMC with two variables v_o and i_c. In this type, two state variables are sensed, the current and voltage of the capacitor as shown in Figure 2.

$$V = V_{ref} - V_o \tag{5}$$

$$\dot{e} = \frac{de}{dt} = -\dot{V_o} = -\frac{1}{C}i_c = -\frac{1}{C}(i_L - \frac{V_o}{R}) \tag{6}$$

$$S = -\frac{1}{C}i_c + \frac{1}{RC}V_o + K(V_{ref} - V_o) \tag{7}$$

$$S = -\frac{1}{C}i_c + (\frac{1}{RC} - K)V_o + KV_{ref} \tag{8}$$

Where Ki, Ku are the coefficients of a sliding surface correspond to i_c and v_c respectively.

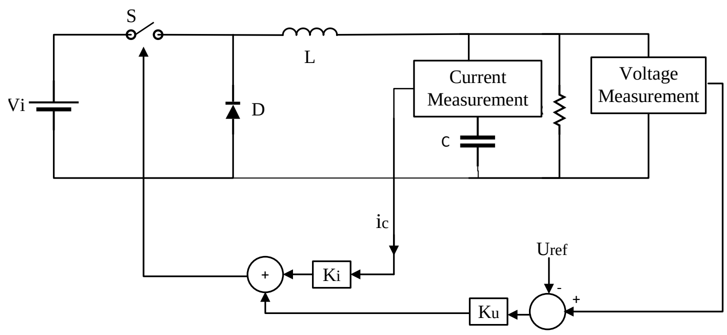


Figure 2. SMC with two variables v_o and i_c

Type III: SMC with two variables v_o and i_L [25]. In this type, the current of the inductor and the output voltage are sensed, as it is illustrated in Figure 3.

$$S = K_i e_1(t) + K_u e_2(t) \tag{9}$$

where Ki, Ku are the coefficients of a sliding surface correspond to i_L and v_c respectively.

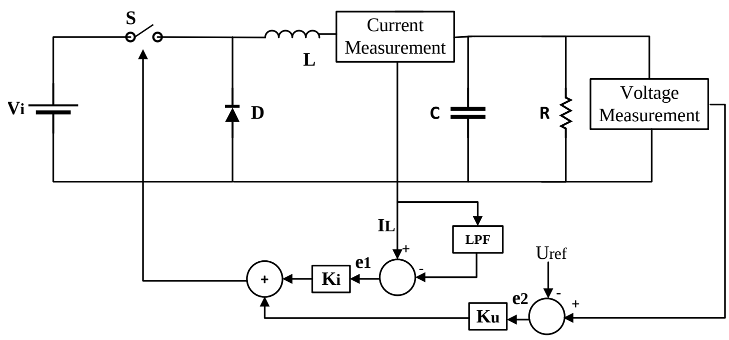


Figure 3. SMC with two variables v_o and i_L

Type IV: ISMC schematic is drawn in Figure 4. The sliding coefficients are created depending on the required response of the converter circuit.

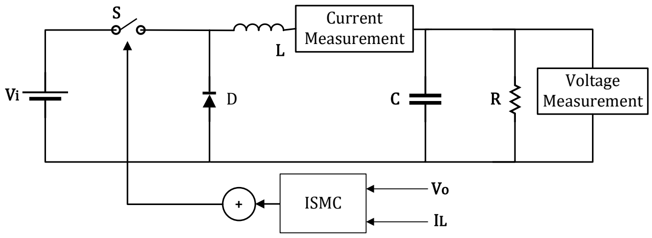


Figure 4. Integral sliding mode controller

ISMC for DC/DC converter is based on PWM scheme. PWM compares the control signal to a saw-tooth waveform to generate gate pulses with the same frequency as the desired switching frequency. ISMC has three parameters, X_1, X_2, and X_3, where X_1 is a load voltage error, X_2 is a voltage error' rate of change, and X_3 is an integration of voltage error. The parameters are described in its state space as in (10) [22]:

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{1}{RC} & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{V_s}{LC} \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ \frac{V_o}{LC} \\ 0 \end{bmatrix} \tag{10}$$

The sliding surface for ISMC is expressed as in (11):

$$\begin{aligned} &\sigma: \lambda_1 x_1 + \lambda_2 x_2 + \lambda_3 x_3 = 0 \\ &\sigma: \frac{\lambda_1}{\lambda_2} x_1 + x_2 + \frac{\lambda_3}{\lambda_2} x_3 = 0 \end{aligned} \tag{11}$$

Where λ_1, λ_2, and λ_3 are sliding coefficients. The condition, $\sigma\dot{\sigma} < 0$, $V(s) = \sigma^2/2$, has been defined. On the basis of this, the following inequality must be satisfied as in (12) [20]:

$$\dot{\sigma} \begin{cases} \alpha_1 < 0, for \ \ \sigma \to 0^+ \\ \alpha_1 > 0, for \ \ \sigma \to 0^- \end{cases} \tag{12}$$

Using the values from (10) and (11) to obtain (13):

$$0 < \left(\frac{1}{RC} - \frac{\lambda_1}{\lambda_2}\right) Li_c + \frac{\lambda_3}{\lambda_2}(V_{ref} - V_o)LC + V_o < V_s \tag{13}$$

By setting the derivative of the sliding surface to zero $\dot{\sigma} = 0$, equivalent control, u_{eq} can be determined as in (14):

$$u_{eq} = \frac{\left(\frac{1}{RC} - \frac{\lambda_1}{\lambda_2}\right) Li_c + \frac{\lambda_3}{\lambda_2}(V_{ref} - V_o)LC + V_o}{V_s} \tag{14}$$

Changing (13) to the equivalent control action results in (15):

$$0 < d = \frac{V_{control}}{V_{saw-tooth}} = \frac{{u_{eq}}^*}{V_s} < 1 \tag{15}$$

where ${u_{eq}}^* = \left(\frac{1}{RC} - \frac{\lambda_1}{\lambda_2}\right) Li_c + \frac{\lambda_3}{\lambda_2}(V_{ref} - V_o)LC + V_o$

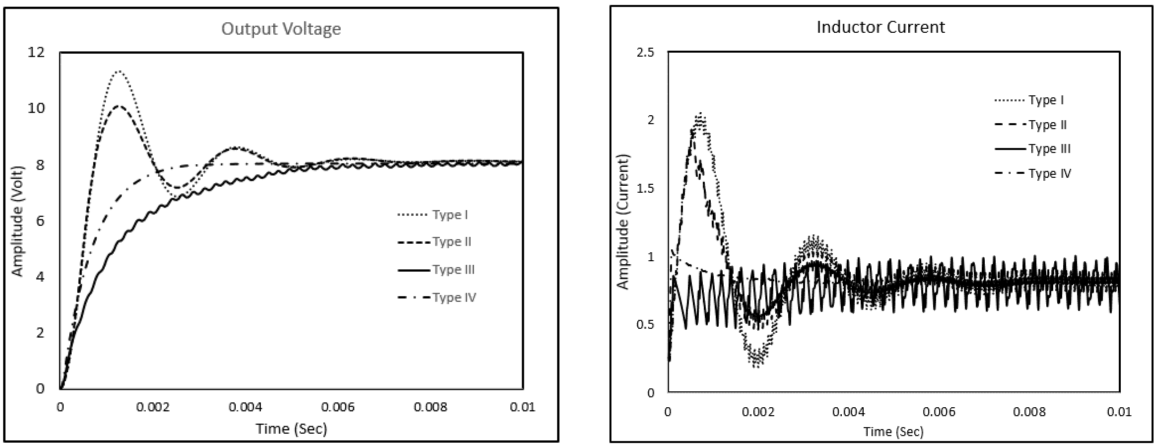
3. RESULTS AND DISCUSSION

The DC/DC buck converter is aimed for a ripple of output voltage less than 0.3% and operates at frequency about 20 kHz. The parameter set strategies are Vin=24 V, L=1.776 mH, C=86 uF, and R=10 Ω. The performance of DC/DC buck converter using the CSMC and ISMC, they have been examined and their validity to be tested by analyzing and representing maximum overshoot, peak, rise, and steady state times. Figure 5 represent the simulation of time response waveform of the system when using the DC/DC buck converter (type I), conventional SMC (type II), low pass filter (LPF) with SMC (type III), and ISMC (type IV) as illustrated in Table 1.

The results demonstrate that, the DC/DC buck converter without SMC (type I) has an overshoot of 40.14%, undershoot of 9.793%, a tr of 527 usec, a tp of 1.24 msec, and a ts of 4.848 msec. Whereas, introducing converter based on conventional SMC with two variables, i_c and Vout, (type II) has demonstrated better performance as the figure change to an overshoot of 24.375%, an undershoot of 7.32%, a tr of 496 usec, and a ts of 4.694 msec. Moreover, introducing converter based on CSMC with two variables, i_L and Vout, (type III) has demonstrated much better performance than the previous method, as the response change to an undershoot of 3.64%, a tr of 3.253 msec, and a ts of 19.277 msec. Finally, presenting converter based on ISMC (type IV) which has demonstrated the best performance among the previous methods, as the figure change to demonstrate an undershoot of 1.991%, a tr of 1.39 ms, and a ts of 1.85 msec. It is interesting to notice there is no overshoot when using conventional slide mode with two variables (iL and Vout) and ISMC. Figures 5(a) and (b) illustrates output voltage and inductor current in ISMC respectively. It is noticeable that both the voltage and current has a lower ts and faster response than other compared methods to reach the steady state with a lowest ripple value.

Table 1. The performance of different types of SMC and PWM for DC/DC converter

Type	V_{in} (V)	V_{out} (V)	t_r (usec)	t_S (msec)	t_P (msec)	Undershot (%)	Overshot (%)
I	24	8	527	4.848	1.24	9.793	40.194
II	24	8	496	4.694	1.23	7.865	24.375
III	24	8	9801	19.277	-	3.64	-
IV	24	8	1390	1.85	-	1.991	-

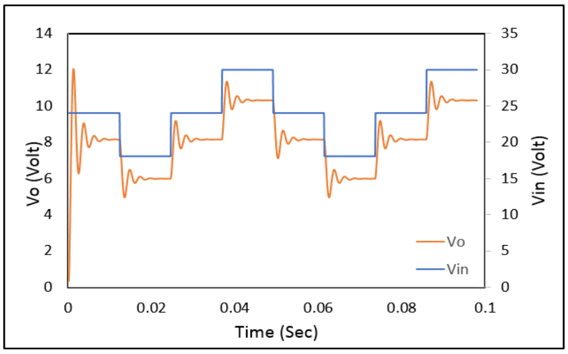


(a) (b)

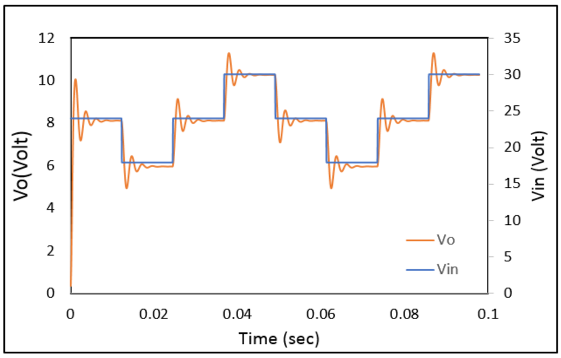
Figure 5. Time response of the compared four types of control to (a) output voltage and (b) inductor current

It is interesting to notice the differences in the output voltage corresponding to change of input voltage for the four types of control of DC/DC buck converter. Three types of SMC beside the PWM control without SMC. It can be easily observed from Figures 6(a) and (b) that the input voltage is started from 18 V, 24 V to 30 V at interval time t=12.5 ms. Figures 6(a) and (b) show a high effect of variation of the input voltage on the output voltage. While Figure 6(c) shows a limited effect of variations of the input voltage on output voltage. This system shows elimination of overshoot, steady state error, minimizing settling time, and causing less chattering on the output voltage. Finally, Figure 6(d) shows that, by using the ISMC, the best performance can be acquired. It is quite obvious to notice the lowest impact of input voltage variation and load changing on the output voltage with very limited chattering.

Dynamic performance and robustness of the four types have been checked in regard to load variation. The simulation results for the four topologies with sudden changes of load on steps 5 Ω, 10 Ω, and 15 Ω at interval of 12.5 msec have been examined. The simulation results demonstrate that the type I (fixed frequency PWM) and type II CSMC are vulnerable to high effect of output voltage during load resistance changing as shown in Figures 7(a) and (b). While, the type III LPFSMC has a stable output voltage and it is not affected by change of the load resistance. However, the system still has a considerable chattering in its voltage as detailed in Figure 7(c). Finally, type IV is presenting ISMC, which has demonstrated the best performance among the other methods in terms of smooth output voltage with no overshoot as shown in Figure 7(d).



(a)



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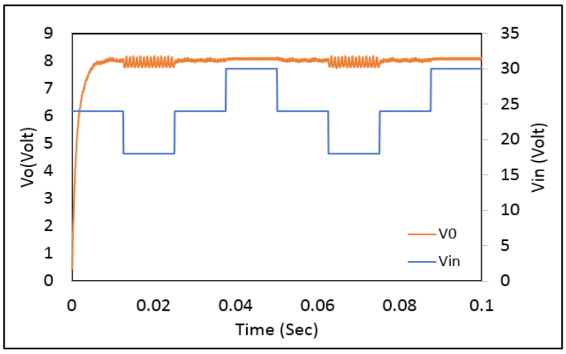
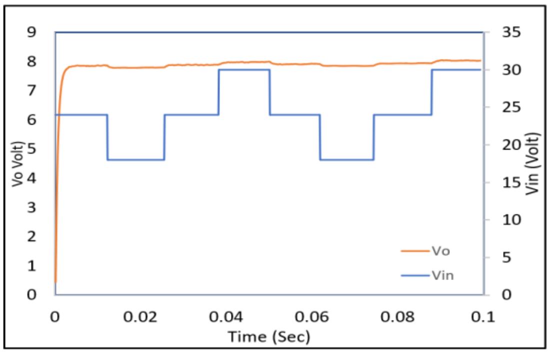
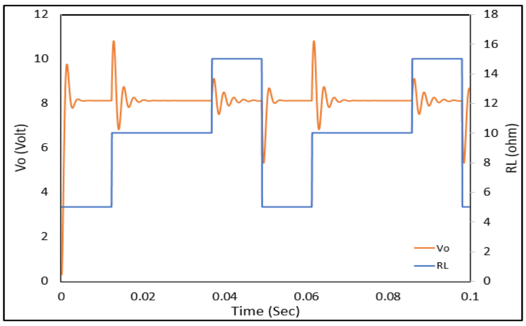


(c)

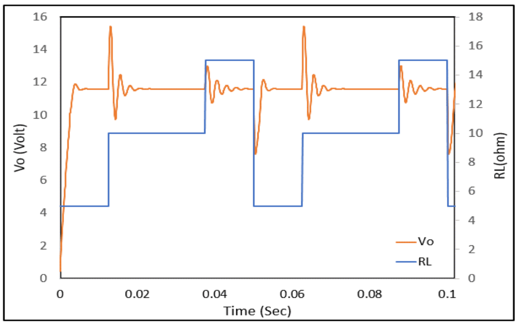


(d)

Figure 6. Time responses of output voltage, corresponding to input voltages from 18 V to 30 V for DC/DC buck converter with (a) PWM-type I, (b) CSMC-type II, (c) LPFSMC-type III, and (d) ISMC-type IV



(a)



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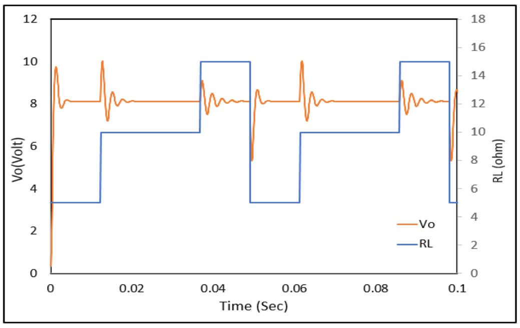
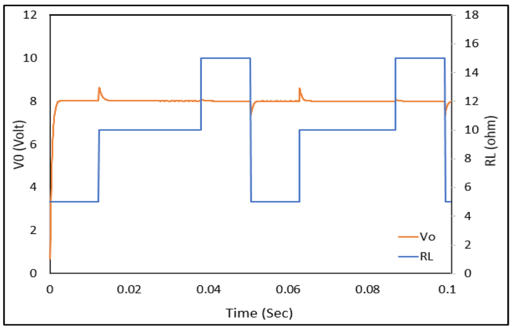


(c)



(d)

Figure 7. Time responses of output voltage corresponding to load resistances from 5 Ω to 15 Ω for DC/DC buck converter with (a) PWM (type I), (b) CSMC (type II), (c) LPFSMC (type III), and (d) ISMC (type IV)

4. CONCLUSION

In this paper, the basic PWM and three different types of SMC controllers for DC/DC buck converter have been examined by investigating the transient and steady state responses of the output voltages, inductor, and capacitor current. The results of analysis and simulation of proposed methods are compared by different parameters and operating conditions. It is found that the ISMC control strategy has the best dynamic performance over the other tested methods, by minimizing the settling time and chattering of the output voltage. The simulation result demonstrates that the voltage regulation of ISMC has a stable response under rapid changes of the load variation. Also, it is proven that, the ISMC is less sensitive to disturbances caused by power supply variations. For future development, inorder to get better performance, a double ISMC will be adopted in a DC to DC buck boost converter.

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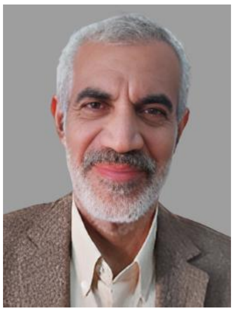

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