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To cite this article: Muhanad D. Almawlawe *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **518** 042016

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Performance Comparison Between Different Control Algorithms in Regulating DC- Voltage

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Abstract. This paper compares three different techniques that control the output voltage of a DC-DC converter working in continuous conduction mode , the first technique is the proportional-Integral-derivative controller, the second one is the fuzzy logic controller, and finally the digital sliding mode controller. The sensed output voltage of the converter is considered as the variable value that should be controlled. The designed control techniques are simulated in MATLAB/Simulink software and the dynamical response of each technique is derived in order to choose the adequate control technique.

1. Introduction

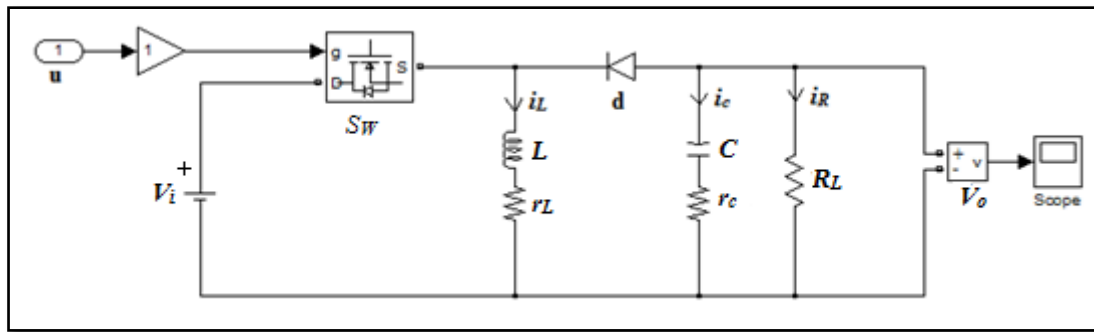
The DC-DC converters are circuits that can be considered as equivalent circuits of the transformer With an adjustable winding ratio, the transformers can increase, reduce the AC voltage, as well, the DC-DC converters can reduce, increase the Dc voltage. The primary goal of the DC-DC converter is to ensure a stable DC voltage supply needful for electrical devices as in the renewable energy systems, communication systems, microprocessors, dishwashers, automobile industry and others. The linear control algorithms such as PID controllers, root- locus techniques, Ziegler-Nicolas algorithm is unable to ensure acceptable results under parameter or load variation [1], [2]. The DC-DC converters are nonlinear and time-variant systems, so we need to consider a nonlinear control techniques that enables the DC-DC converter to be robust to parameter variations and external disturbances. The fuzzy logic control technique which its work based on linguistic rule can decrease the nonlinearity of the plant with no need for accurate mathematical model, this technique is designed to change the duty cycle of the PWM signal of the converter [3], [4]. Fuzzy logic control has many advantages against the classical controller such as simplicity of control, low cost and the possibility to design without knowing the exact mathematical model of the process. The digital sliding mode control technique depends upon the plant output measurements and the digital signal processing (DSP) that enables the easy and fast realization of SMC algorithms, Sliding mode control (SMC) is a nonlinear control method that changes the dynamics of a nonlinear system by applying a discontinuous control signal that forces the system to slide along a predefined hypersurface [5], [6].

This paper considers the design of DC-DC Buck-Boost converter in the three mentioned control techniques, the comparison is performed using MATLAB/Simulink software to establish the improvements of each technique.

2. Model of Buck-Boost Converter

The main circuit of the Buck-Boost DC-DC converter is presented in Figure 1[1]:



**Figure 1.** Basic Buck-Boost circuit

The mathematical model of the Buck-Boost DC-DC converter can be derived from Figure 1, depending upon the switching action:

1- When switch S_w is on OFF position:

$$\left. \begin{aligned} C \frac{dV_o}{dt} &= -\frac{V_o}{R_L + r_c} \\ L \frac{dI_L}{dt} &= V_i - (r_L + r_p)I_L \end{aligned} \right\}, 0 < t < dT \quad (1)$$

2- When switch S_w is on ON position:

$$\left. \begin{aligned} C \frac{dV_o}{dt} &= -\frac{V_o}{(R_L + r_c)} + \frac{r_L}{(R_L + r_c)} I_L \\ L \frac{dI_L}{dt} &= \frac{R_L}{(R_L + r_c)} V_o + (r_c \parallel r_L - rd) I_L \end{aligned} \right\}, dT < t < T \quad (2)$$

The continuous-time model of converter in state-space is:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + BV_i(t), \\ V_o(t) &= Cx(t) \end{aligned} \quad (3)$$

Where:

$$A = \begin{bmatrix} -\frac{1}{C(R_L + r_c)} & \frac{R_L(1-D)}{C(R_L + r_c)} \\ -\frac{R_L(1-D)}{L(R_L + r_c)} & \frac{(1-D)(r_c \parallel R_L - r_d) - r_L - Dr_p}{L} \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{D}{L} \end{bmatrix}, C = \begin{bmatrix} \frac{R_L}{(R_L + r_c)} & (1-D)r_c \parallel R_L \end{bmatrix} \quad (4)$$

So, the transfer function of the Buck-Boost converter working on continuous mod is:

$$G(s) = \frac{V_o(s)}{V_i(s)} = \frac{D(1-D)}{LC(1+\alpha_c)} \cdot \frac{C\alpha_c s + 1}{s^2 + \frac{1}{(1+\alpha_c)} \left(\frac{1}{R_L C} - \frac{R_L \beta}{L} \right) s + LC(1+\alpha_c)^2(1-D)^2 - \beta} \quad (5)$$

Where:

$$\begin{aligned} \beta &= (1-D)(\alpha_c - \alpha_d) - (\alpha_L + D\alpha_s)(1+\alpha_c), \\ \alpha_c &= \frac{r_c}{R_L}, \quad \alpha_d = \frac{r_d}{R_L}, \quad \alpha_s = \frac{r_s}{R_L} \end{aligned} \quad (6)$$

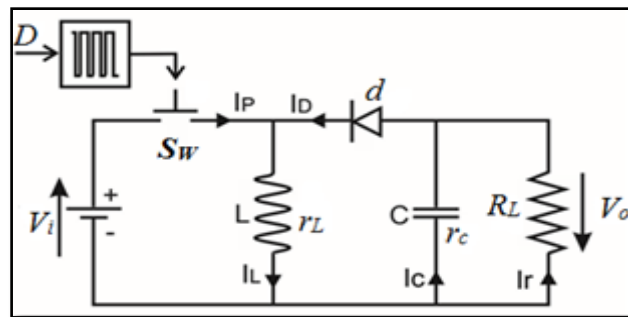
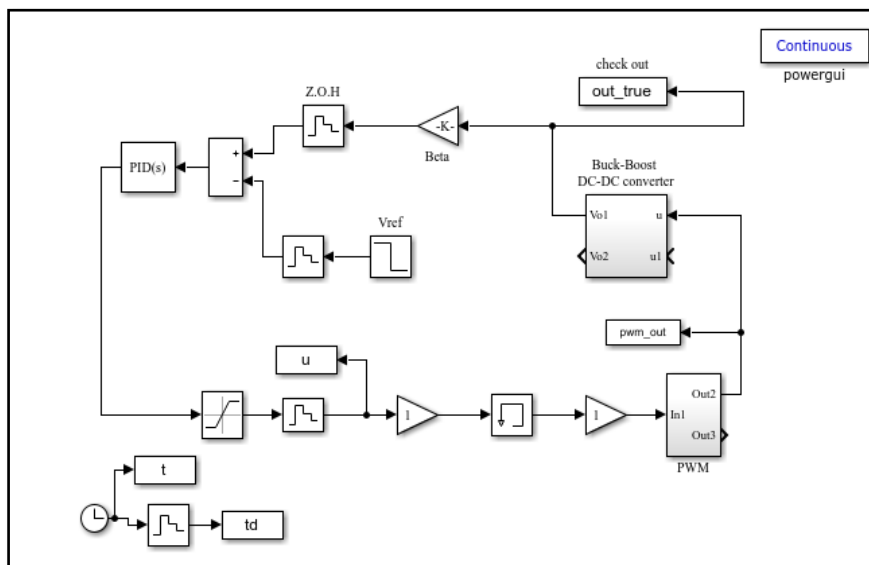
The values of the component of the Buck-Boost converter are given in Table 1:

Table 1. Components of Buck-Boost Converter

Description	Parameter	Nominal Value
Output voltage	V_o	21V
Capacitance	C	50 μ F
resistance	r_c	0.15
Inductance	L	270 μ H
resistance	r_L	0.5
Load Resistance	R_L	20 Ω
Switching frequency	f_s	100 kHz
Duty cycle	D	0.5

3. Proportional-Integral-Derivative Controller

The conventional Buck-Boost converter is given in Figure 2, while the Buck-Boost converter with PID controller is given in Figure 3:

**Figure 2.** Conventional Buck-Boost Converter**Figure 3.** Buck-Boost Converter with PID controller

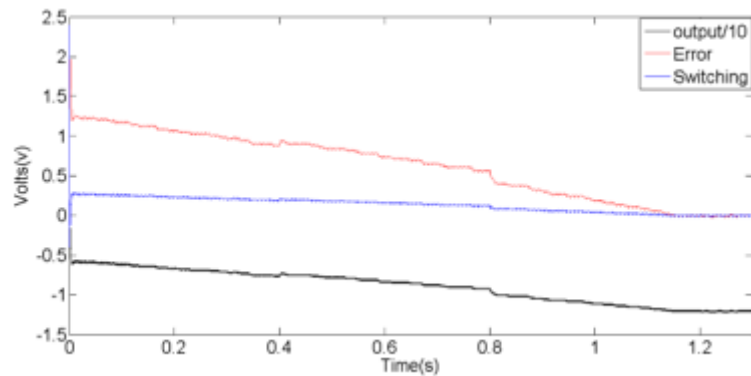
The transfer function of the PID controller is:

$$G(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s = K_p \left(1 + \frac{1}{sT_i} + T_d s \right) \quad (7)$$

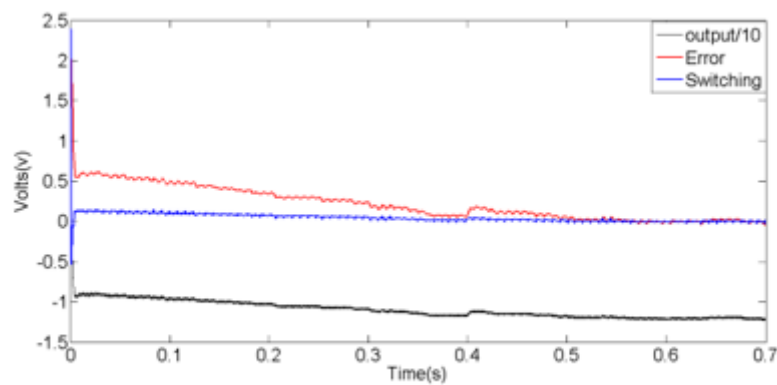
Where : K_p , K_i , and K_d are the proportional , integral, and differential gains, respectively.

$$T_i = \frac{K_p}{K_i}, \text{ and } T_d = \frac{K_d}{K_p} \quad (8)$$

Depending on the previous transfer functions we can simulate the given converter using MATLAB/Simulink software to get the output voltage for both conventional converter and converter using PID controller as in Figure 4:



a) Conventional Buck-Boost Converter



b) Buck-Boost converter with PID Controller

Figure 4. The output voltage of: (a) conventional Buck-Boost converter, (b) converter with PID controller

4. Fuzzy Logic Controller

The Buck-Boost converter with FLC is given in Figure 5 [5], [6]:

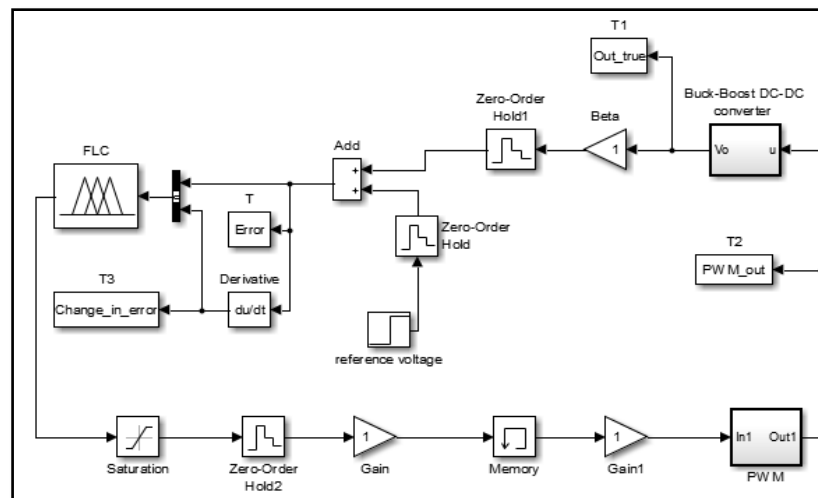


Figure 5. Buck-Boost Converter with fuzzy logic controller

In this approach the output voltage is controlled by FLC, this variable (output voltage) is considered as linguistic variables instead of numerical variables, this process is called fuzzification see Figure 6, Figure 7, and Figure 8. The inputs for the FLC are the error $e(k)$ and change in error $Ce(k)$, the error $e(k)$ is established by comparing the actual voltage $Vo(k)$ with the reference voltage $V_{ref}(k)$. The change in error $Ce(k)$ is obtained from the error $e(k)$, and previous error $e(k)$.

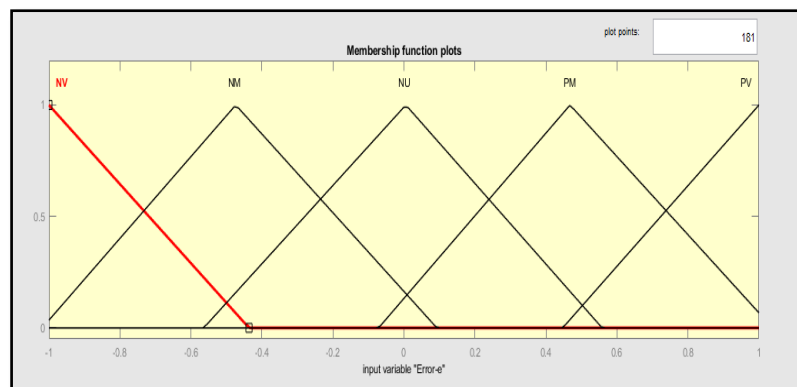


Figure 6. First input for FLC(Error)

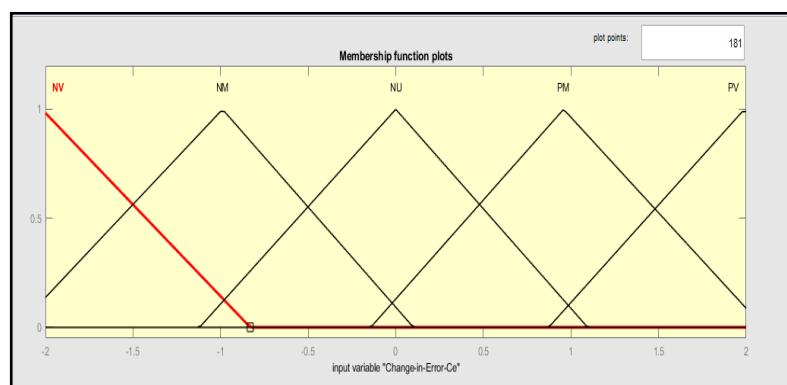


Figure 7. Second input for FLC (Change in error)

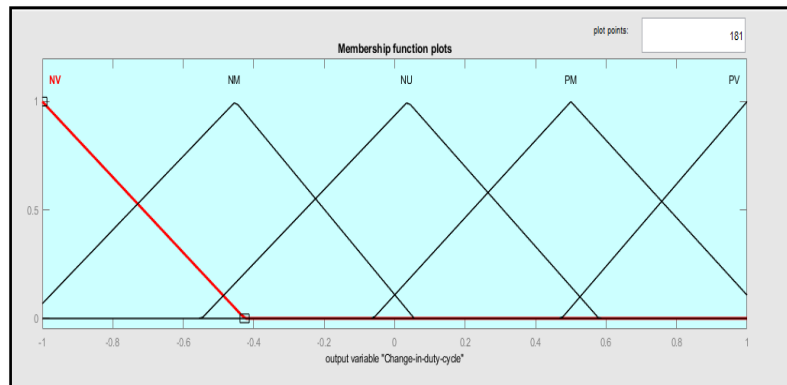


Figure 8. Output of the FLC (Change in duty-cycle)

The rule table for the designed fuzzy controller is given in the **Table 2**. The element in the first row and first column means that If an error is NV, and change in error is NV then output is NV.

Table 2. Fuzzy rules

Error(e)	Change in error (Ce)				
	NV	NM	NU	PM	PV
NV	NV	NV	NV	NM	NU
NM	NV	NV	NM	NU	PM
NU	NV	NM	NU	PM	PV
PM	NM	NU	PM	PV	PV
PV	NU	PM	PV	PV	PV

The next step is to convert the linguistic variables in to a numerical variable (defuzzification), the defuzzified output is the duty cycle $D(k)$. The change in duty cycle $\Delta D(k)$ can be obtained by adding the pervious duty cycle $pD(k)$ with the duty cycle $D(k)$ which is given in equation:

$$\Delta D(k) = D(k) + pD(k) \quad (9)$$

We can illustrate the change in duty cycle in 3D as in Figure 9:

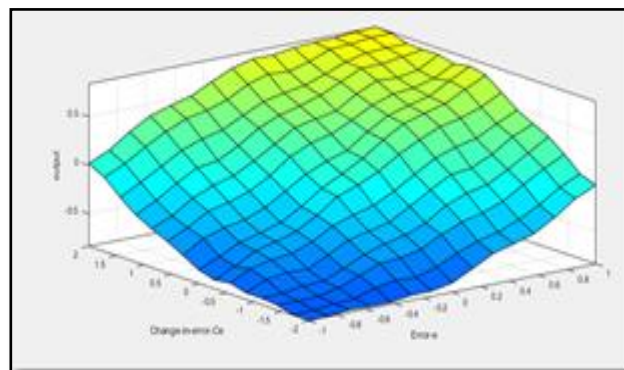


Figure 9. Output of the FLC(Change in duty-cycle)

Finally, by using fuzzy logic controller considered previously we can simulate the output voltage as in Figure 10.

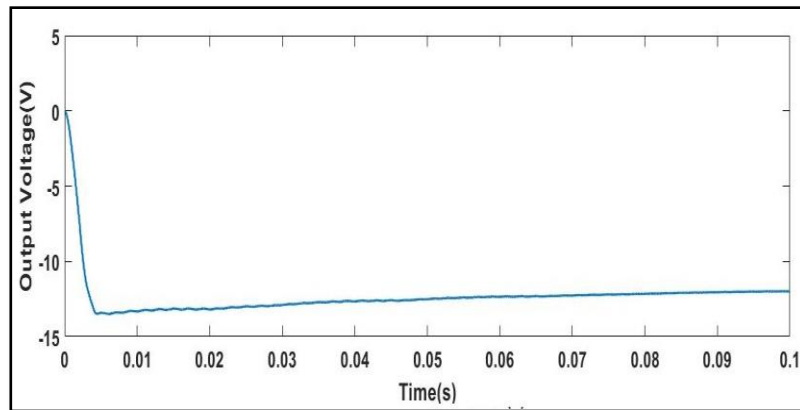


Figure 10. The output voltage of the Buck-Boost converter with FLC controller

5. Digital Sliding Mode Controller

The Schematic diagram for the digital sliding mode controller is shown in Figure 12:

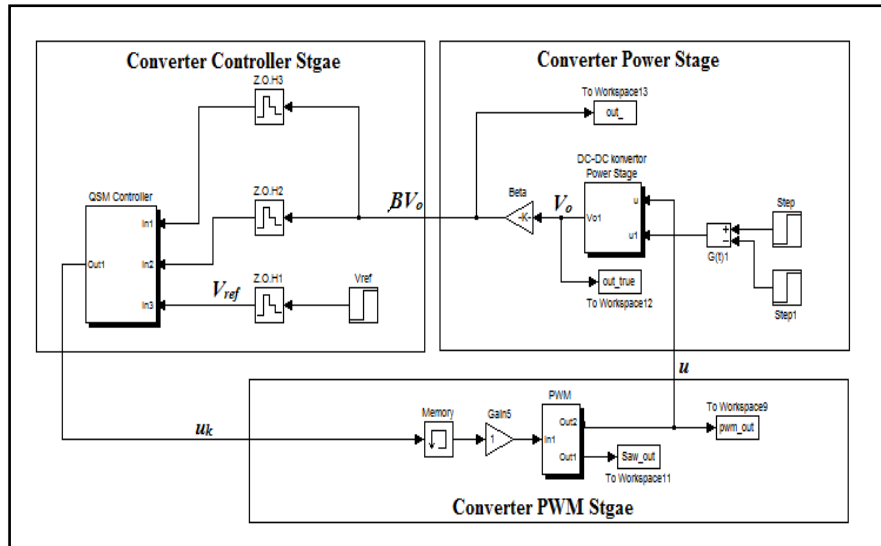


Figure 11. Digital Sliding Mode Controller

If the reference input signal $V_r(k)$ is known in advance, then the proposed control law for the digital sliding mode controller for buck-boost converter is given as in [7], [8]:

$$u(k) = -\frac{F(z^{-1})y(k) - C(z^{-1})V_r(k+1) + \frac{\alpha T}{1-z^{-1}} \text{sgn}(s(k))}{E(z^{-1})B(z^{-1}) + Q(z^{-1})} \quad (10)$$

The switching function is defined as:

$$S(k+1) = C(z^{-1})(y(k+1) - V_r(k+1)) + Q(z^{-1})u(k) \quad (11)$$

Where:

$$C(z^{-1}) = c_0 + c_1 z^{-1} + c_2 z^{-2} \quad (12)$$

$$C(z^{-1}) = (1 - e^{-2\pi f_c T} z^{-1})^2 \quad (13)$$

The stability condition is:

$$B(z^{-1})C(z^{-1}) + A(z^{-1})Q(z^{-1}) = 0 \quad (14)$$

The polynomials $E(z^{-1})$ and $F(z^{-1})$ are the solutions of Diophantine equation, $C(z^{-1})$ is a polynomial with all zeros inside the unit disk of z -plane, and the digital sliding mode control is based on the sensed output voltage βV_o which is compared with the referent voltage V_r , resulting in an error signal that is only fed to the digital SM controller. The signal $u(k)$ is fed to the PWM stage, where is compared with the ramp signal, providing a PWM signal u that drives the switch S_w . As in the average dynamics of system with digital SM control is equivalent to the average dynamics of PWM controlled system, implying that the equivalent control $u_{eq}(k)$ in SM corresponds to the duty cycle control signal D of PWM stage:

$$0 < D = \frac{u(k)}{V_{ramp}} < 1 \quad (15)$$

The output voltage of the digital sliding mode controller used to regulate the output voltage of the Buck-Boost converter is illustrated in Fig. 11. The input voltage of the Buck-Boost converter is 12V, and the output voltage is about 12V. The nominal duty-cycle D is 0.5, the settling time is about 0.01s.

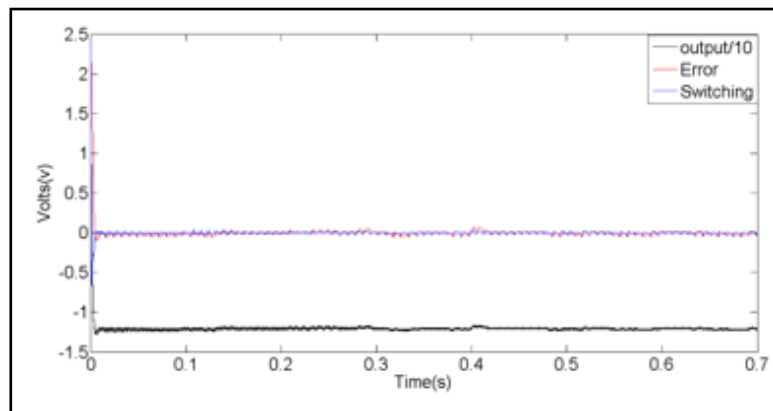


Figure 12. Output of the DSMC for Buck-Boost converter

6. Conclusion

Using MATLAB/Simulink software the output voltage of a Buck- Boost DC-DC converter is controlled using three different control strategies, the results are compared with the conventional DC-DC converter. The conventional converter has steady-state time about 1.19 s, the Buck-Boost with PID controller has a steady-state time about 0.4s while the converter with fuzzy logic controller has the settling time about 0.025s, and the converter with digital sliding mode has 0.01s. Depending on this fact we can conclude that DSMC is most suitable because of its good performances, low rise time, quick settling time and stable output.

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