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ENHANCING STABILITY AND REGULATION OF OUTPUT VOLTAGE IN BOOST CONVERTERS WITH LEARNING SLIDING MODE CONTROL

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ABSTRACT

Although DC to DC convertors might be considered as the most widely used circuits in power electronic, where a specific DC output voltage must be stabilized to a specific desired level, yet theses circuits unfortunately exhibit a nonlinear behavior. The nonlinearity in these circuits is primarily caused by the power switch, varying input voltages and loads, resulting in a converter instability, large overshoot, oscillations, and extended settling times. To mitigate these problems, a learning sliding mode control (LSMC) was introduced and compared with the proportional integral derivative sliding mode control (PIDSMC) fuzzy logic controller (FLC) as well. The study demonstrated that the LSMC provides a smooth output voltage, without chattering, compared with PIDSMC and FLC. Moreover, formulating LSMC might be considered a novel controlling method for DC to DC convertors as the LSMC represents an advancement in the control strategies for stabilizing output voltages in power electronic circuits. By comparing LSMC with classical PIDSMC and FLC, the paper provides a novel analysis of the effectiveness of different control approaches in addressing nonlinearity and instability in DC to DC converters.

KEYWORDS

DC to DC converter, Sliding mode control, Learning sliding mode control, Proportional integral derivative sliding mode control.

1. INTRODUCTION

DC-DC convertors are electronic circuits that change voltage level of DC supplies by altering the duty ratio of the primary circuits' switches. Various applications use DC-DC convertors including switched mode power provisions, adaptable speed triggers, and uninterruptible energy sources (Rubaai and Chouikha, 2004). Since They are nonlinear systems, they propose a big challenge for control design. Classical control methods cannot respond satisfactorily to variations in operating point and load disturbances, despite being designed at a nominal operating point. They frequently underperform under substantial load fluctuations or parameters (Dhali et al., 2012). The sliding mode control (SMC) are commonly used for such converters due to their robust, low implementation difficulty, and greater durability and rapid reaction to unintentional changes in load and parameter (internal noise and external disturbances). The main advantages of this system are its insured stability and robustness against parameter, line, and load uncertainties (Utkin, Guldner and Shi, 2017). In addition, as a controller with a large degree of pliability in its design, comparatively to other nonlinear controllers' types, SMC is relatively simple to implement. This property makes it very proper for nonlinear control implementations (Edwards and Spurgeon, 1998).

Various methods are suggested in the literature review to design a SMC. In (Martínez-Treviño et al., 2017), the authors proposed a linear switching surface that reduces inrush current while regulating output voltage to overcome the converter's intrinsically unstable behaviour in both on and off states. To track the problem, the author used a sliding mode control method of providing constant power load to boost converter. In (Taheri et al., 2019),a new general sliding mode controller for a DC-DC converters is proposed that can controls the output voltage.

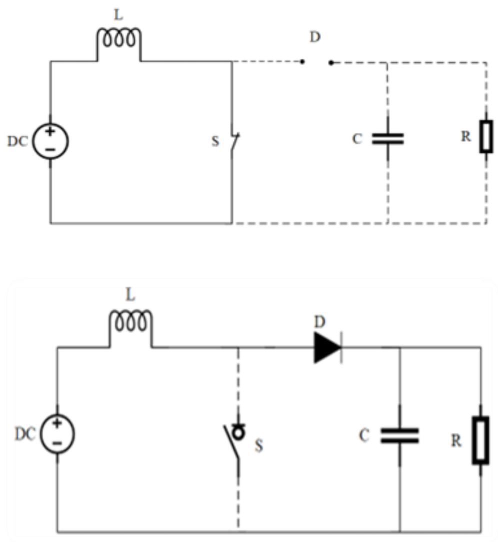
In the steady-state, the proposed controller exhibits zero error for a variety of output voltage references, variable loads, and variable inputs, as well as acceptable dynamic response. In (Al-Qaisi et al., 2019), the author presented a PID sliding mode voltage controller (PID SMVC) for buck converter and used to develop pulse width modulation (PWM). The simulation results obtained from the buck converter system confirmed the SMC controller is a robust controller against load varies and it is less sensitive to disturbances. In (Erokhina et al., 2021), the author presented the operation of the boost DC-DC converter in sliding mode control. The results showed that, despite the oscillatory nature of the transient process, the system with the sliding control method staid stable in both disturbances. In (Dehri and Nouri, 2021) ,the author presented an adaptive sliding mode control on a linear time-varying system with periodic disturbances using only input-output measurements.

In this paper a comparative between PIDSMC, LSMC and FLC has been done by using Simulink MATLAB program and the effectiveness of LSMC in controlling the output voltage of boost converter in terms of varying input voltage and load. The content of this paper is: part 1 present mathematical model of DC-DC convertor, part 2 present SMC in PIDSMC and LSMC, part 3 includes result and discussion, part 4 present comparison of methods and part 5 contains the conclusion.

2. MATHEMATICAL MODEL OF DC-DC BOOST CONVERTER

The fundamental boost converter 'ON' and 'OFF' state circuits are shown in Fig. 1(a)-(b) respectively.

(a)



(b)

Fig. 1. Boost converter equivalent circuit on the (a) ON state and (b) OFF state

During 'ON' state: the inductor is charged through u=1 as defined in (1). There is no current to flow in the capacitor and resistor in this state, where i_d is zero as defined in (2).

$$L\frac{di_l}{dt} = V_i \tag{1}$$

$$\frac{dV_0}{dt} = -\frac{1}{RC}V_o \tag{2}$$

During 'OFF' state:

$$L\frac{di_l}{dt} - V_{out} - V_i = 0 \tag{3}$$

$$i_l - C\frac{dV_o}{dt} - \frac{V_o}{R} = 0 \tag{4}$$

The state derivative of $\dot{X}_1$ and $\dot{X}_2$ in (5) and (6) can be obtained by rearranging (1) and (2). The state space matrix A and B in (7) for boost converter at 'ON' and 'OFF' states can be formulated using (5) and (6).

$$\dot{X}_1 = \frac{V_o}{L}\,(1-u) + \frac{V_i}{L}\,u \tag{5}$$

$$\dot{X}_2 = \frac{i_l}{C}(1-u) - \frac{V_o}{RC}u \tag{6}$$

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\end{bmatrix} = \begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}X_1\\ X_2\end{bmatrix} + \begin{bmatrix}\frac{V_i}{L}\\ 0\end{bmatrix}u_1 \tag{7}$$

where u1 = (1-u)

2.1. Proportional integral derivative sliding mode control (PIDSMC)

The voltage at the output (Vo) from the convertor is managed by SMC. Assuming the convertor runs in CCM, a control variable X in the case of PWM and according to PIDSMC converter can be written as:

$$X_1 = V_{ref} - \beta V_o \tag{8}$$

$$X_2 = \dot{X}_1 = \frac{\beta V_o}{RC} + \int \frac{\beta(V_o - V_i)}{LC}\,dt \tag{9}$$

$$X_3 = \int X_1 dt = \int\left(V_{ref} - \beta V_o\right)dt \tag{10}$$

Where R is a load resistance connected to the boost convertor and β is a voltage divider.

The time differentiation of equations (8), (9) and (10) produce the state-space description required for controller design of the converter.

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \dot{X}_3\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & -\frac{1}{RC} & 0\\ 1 & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ \frac{\beta v_0}{LC} - \frac{\beta v_i}{LC}\\ 0\end{bmatrix}u_1 \tag{11}$$

Where $u_1 = (1-u)$ is the inverse logic of u, and is used particularly for modeling the boost converter and obtaining control signal (V_c):

$$V_c = -K_1 i_c + K_2\left(V_{ref} - \beta v_o\right) + \beta(v_o - v_i) \tag{12}$$

$$K_1 = \beta L\left(\frac{\alpha_1}{\alpha_2} - \frac{1}{R_L C}\right) \tag{13}$$

$$K_2 = LC\left(\frac{\alpha_3}{\alpha_2}\right) \tag{14}$$

Where K_1, K_2 are the closed-loop signal gain constants, and their values can be ccomputed using converter component L, C, and R_L, as well as the values of sliding parameters α_1, α_2, and α_3. By setting S=0 and matching this equation to the normal second order system form, the sliding coefficients can be resolved as in (Kannad, 2015), (Tan et al., 2005):

$$S = \alpha_1 X_1 + \alpha_2 \frac{dX_1}{dt} + \alpha_3 \int X_1 = 0 \tag{15}$$

Where $W_n = \sqrt{\frac{\alpha_3}{\alpha_2}}$ is the undamped natural frequency, $\zeta = \frac{\alpha_1}{2\sqrt{\alpha_3 \alpha 2}}$ is the damping ratio,

$f_{BW} = \frac{1}{2\pi}\sqrt{\frac{\alpha_3}{\alpha_2}}$ is the bandwidth of controller's response, $\frac{\alpha_1}{\alpha_2} = 4\pi f_{BW}$, for $\zeta = 1$,

and $\frac{\alpha_3}{\alpha_2} = 4\pi^2 f_{BW}^2$.

The PIDSMC Simulink model for the boost converter is shown in Fig. 2.

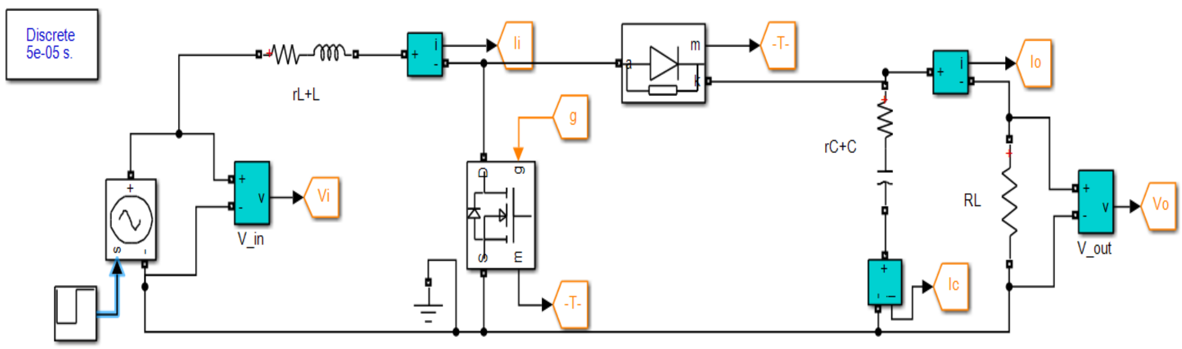


Fig. 2. Simulink model of the PIDSMC boost converter

2.2. Learning slide mode control (LSMC) robust approach for boost convertor

The proposed control algorithm is similar to the recursive learning method (Do et al., 2013), an associated learning term and a recent control signal make up the control signal as shown in Fig. 3. According to the latest term of stability of the closed-loop system, the learning term searches for the sliding surface and adjusts the stability and convergence, which it can correct the control signals if the closed-loop system is unstable. So, the Lyapunov function's gradient value is decreased from a positive to a negative value, causing the closed-loop trajectory to reach and maintain a sliding state.

Consider the following tracking error as in Equation (8), where V_{ref} is the reference voltage and V_o is the output voltage of the boost converter and the sliding variable is defined in Equation (15), then the time derivative of the sliding variable $s(t)$ is expressed as:

$$\begin{aligned}\dot{s}(t) &= f_1(x,t) + f_2(x,t)u(t) + \lambda\left(\delta_f(t)\right) \\ &= f(t) + f_2(x,t)u(t) \end{aligned} \tag{16}$$

where $\lambda\left(\delta_f(t)\right)$ is unmodeled function.

Let $f_2(x,t) = b$

$$f(t) = f_1(x,t) + \lambda\left(\delta_f(t)\right) \tag{17}$$

The sliding mode learning controller which controls signal has been included unmodeled function to eliminate the effect of disturbances, is proposed as follows:

$$u(t) = u(t-\tau) - \Delta u(t) \tag{18}$$

Where correction term $\Delta u(t)$ is defined as:

$$\Delta u(t) = \begin{cases} \frac{1}{bs(t)}\left(\alpha\hat{\dot{V}}(t-\tau) + \beta|\hat{\dot{V}}(t-\tau)|\right) & \text{for } s(t) \neq 0 \\ 0 & \text{for } s(t) = 0 \end{cases} \tag{19}$$

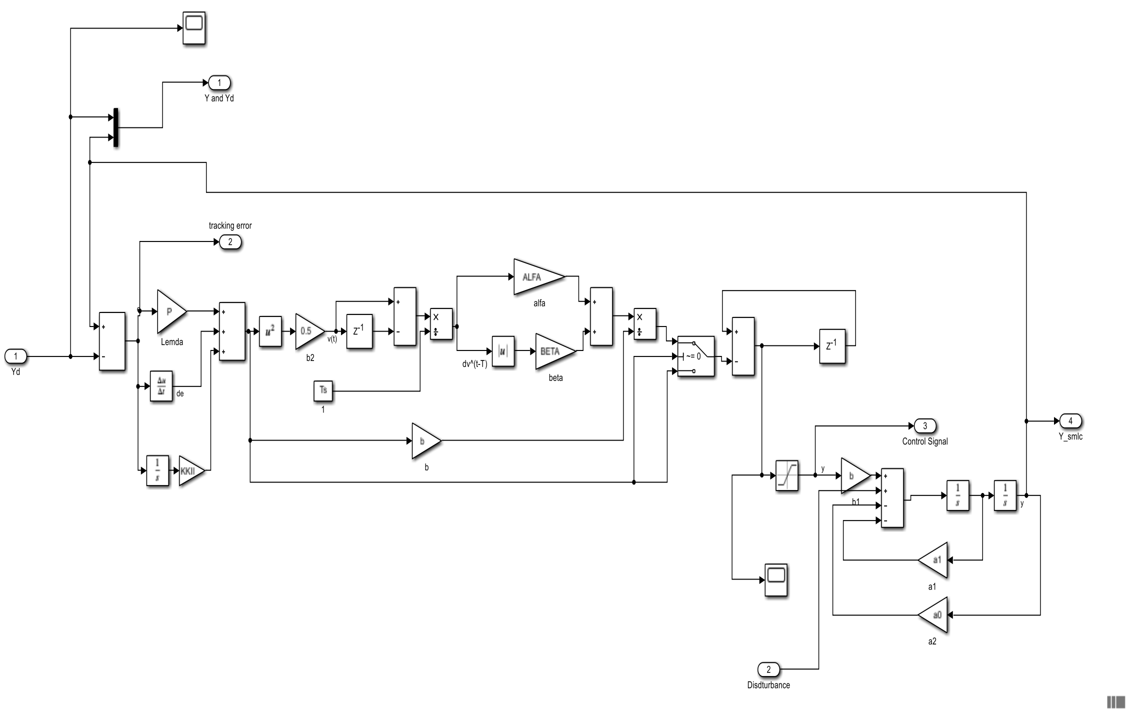


Fig. 3. LSMC Simulink model for the boost converter

Where τ is the delay of time, $\hat{\dot{V}}(t-\tau)$ is the estimated derivative of the delayed Lyapunov candidate function (i.e., $V(t-\tau)$ = 0.5 s$(t-\tau)^2$) which is defined as(Xu and Yan, 2004),(Man et al., 2011):

$$\hat{\dot{V}}(t-\tau) = \frac{V(t)-V(t-\tau)}{\tau} \quad (20)$$

Meanwhile, α and β are the control parameters to be determined. It should be noted that the minimal value of the time delay τ is assumed to coincide with the sampling time for actual implementation. If τ is sufficiently small, it is reasonable to assume that:

$$sig\,n\left(\hat{\dot{V}}(t-\tau)\right) = sign\left(\dot{V}(t-\tau)\right) \quad (21)$$

$$\left|\dot{V}(t-\tau) - \hat{\dot{V}}(t-\tau)\right| < \mu\left|\hat{\dot{V}}(t-\tau)\right| \quad (22)$$

For $\hat{V}(t-\tau) \neq 0, \dot{V}(t-\tau) \neq 0$, and $0 < \mu \ll 1$.

Based on inequality (22) the deviation between the gradient of the Lyapunov function and its approximation is minimal since τ is sufficiently small. It appears that (18) and (19) indicate that u (t) is a continuous signal for s (t) ≠0. If $s(t) = 0$, $u(t)$ is continuous at all points. The presented SMLC in (18) is continuous at every moment in the state space(Do et al., 2013)–(Hadi, Alamili and Abbas, 2023)-(Man, Zhang and Jin, 2012).

2.3. Design fuzzy logic controller

Fuzzy logic controllers (FLC) are nonlinear controllers that make decisions based on imprecise or uncertain information using fuzzy logic. Based on fuzzy set theory, it uses linguistic variables and fuzzy sets to represent uncertain and vague concepts. An FLC maps a system's input variables to a set of fuzzy sets using membership functions, and then maps the fuzzy input variables to fuzzy output variables using fuzzy rules. In order to obtain crisp control inputs, the fuzzy output variables are defuzzified. "If-then" statements represent fuzzy rules derived from expert knowledge or experimental data. A fuzzy output is produced by combining antecedent fuzzy sets using fuzzy logic operators (e.g. AND, OR). A Mamdani or Takagi-Sagano fuzzy model is commonly used to represent the resulting fuzzy set. The FLC uses fuzzy sets and fuzzy logic to make decisions regarding the inputs and outputs of the system in order to handle imprecise and uncertain information. As opposed to conventional linear controllers, which can be susceptible to system uncertainties and disturbances, this enables a more adaptable and reliable control method. In order to accomplish the desired control aim, the system parameters of an FLC must be tuned along with the fuzzy rules and membership functions. Techniques like simulation or Lyapunov stability analysis can be used to analyze the controller's performance. In general, the idea of an FLC offers the design of flexible and robust controllers that can handle uncertain and imprecise information. Based on the human knowledge of system behaviour, a fuzzy logic control consists of a set of rules.

The simulation model was built in Matlab/Simulink to study the dynamic behaviour of DC-DC converters and the performance of proposed controllers. The fuzzy logic controller can also provide desirable dynamic performance for both small and large signals at the same time, which is impossible with linear control. Thus, fuzzy logic controllers have the potential to improve the robustness of DC-DC converters. In order to adapt to varying operating conditions, fuzzy controllers are designed for this purpose. By using Mamdani-style (and method "min" and centroid defuzzification) fuzzy inference system, a fuzzy logic controller controls the output of boost DC-DC converters. In this fuzzy logic system, error (e) and change of error (de) are the input variables. The duty cycle of PWM output is the single output variable (So, Tse and Lee, 1994).

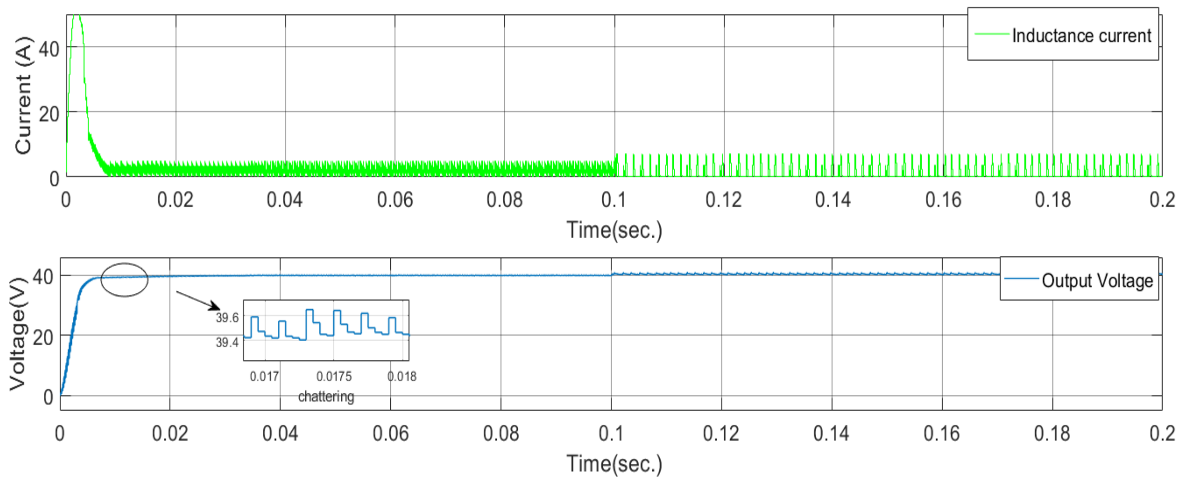
3. SIMULATION RESULTS

It is essential to use feed-back control to keep the output voltage stable even when the input voltage varies. Simulink /MatLab program has been used to obtain the result. Table 1 explain the parameters of boost converter which have been calculated, referred to (Rashid, 2017).

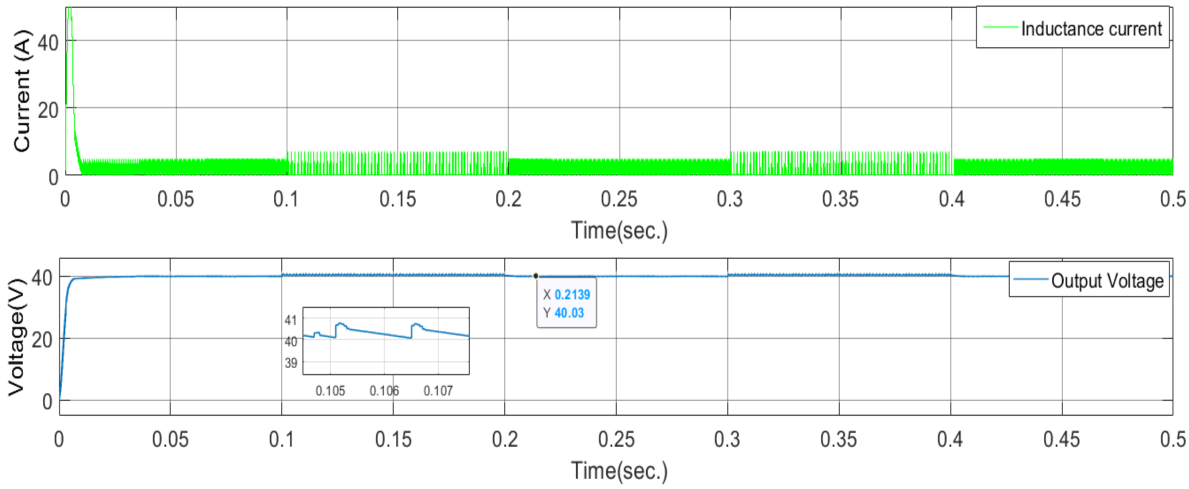
Based on the result in Fig. 4 (a)-(b) the output voltage contains chattering and a steady state error 0.04, the settling time is 5ms in either cases of resistive load 50Ω or 100Ω (full and half load) which is varied with step of 0.1 second.

Table 1. The parameters of boost convertor

Parameter	**Value**	**Unit**
Vi	10-20	V
Vo	40	V
L	1.56	mH
C	267	µF
R	50-100	Ω
F	20	KHz



(a)



(b)

Fig. 4. Output voltage of PIDSMC boost converter with (a) 50Ω and (b) 100Ω resistive load

The control signal of boost convertor generated by PIDSMC is shown in Fig. 5.

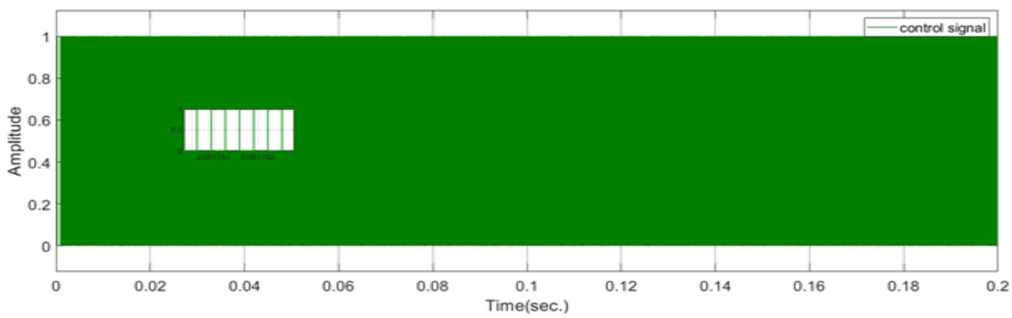


Fig. 5. Control signal of the PIDSMC boost convertor

According to the results shown in Fig. 6, the output voltage is stable with no chattering, the steady-state error is zero, and the settling time is 20ms.

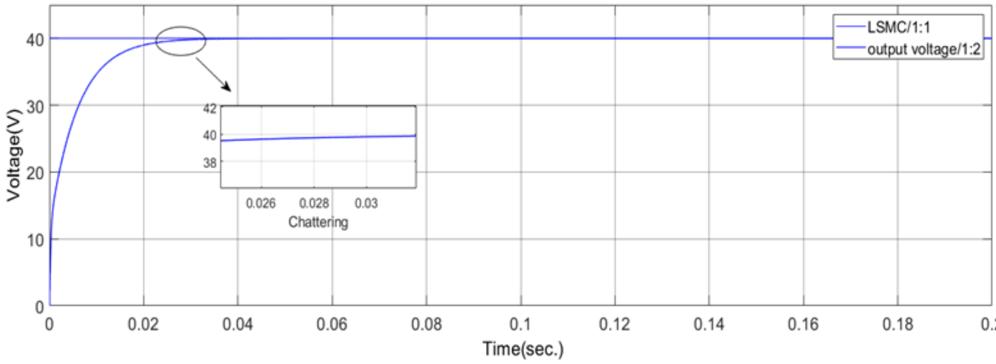


Fig. 6. Output voltage of boost convertor with LSMC

The performance of output voltage chattering and zero steady state error when using LSMC compared with PIDSMC for boost converter is shown in Fig. 7.

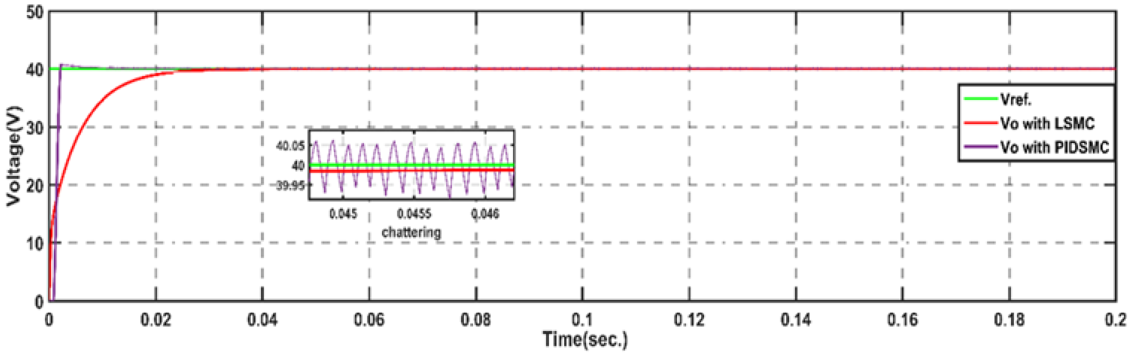


Fig. 7. Output voltage with the LSMC and PIDSMC for boost converter

3.1. Fuzzy logic table rules

Controlling the boost converter's output voltage is an ultimate objective. Fuzzy logic controllers are configured to tackle variable error of output voltage as inputs. Five groups have been formed from these two inputs; NB: Negative Big, NS: Negative Small, ZO: Zero Area, PS: Positive small and PB: Positive Big and its parameter, in this work Mamdani style have been used with centroid de-fuzzification (Raviraj and Sen, 1997), (Viswanathan, Srinivasan and Oruganti, 2002) & (Guo, Hung and Nelms, 2002). These fuzzy control rules for error and change of error can be pointed as shown in Table 2. Fig.8 shows the performance of FLC for the same parameters of the DC- DC boost converter that employed in previous section for variable load (duty cycle, output voltage, and inductor current).

Table 2. Rules for error and change of error

e (de)	NB	NS	Z0	PS	PB
NB	NB	NB	NB	NS	Z0
NS	NB	NB	NS	Z0	PS
Z0	NB	NS	Z0	PS	PB
PS	NS	Z0	PS	PB	PB
PB	Z0	PS	PB	PB	PB

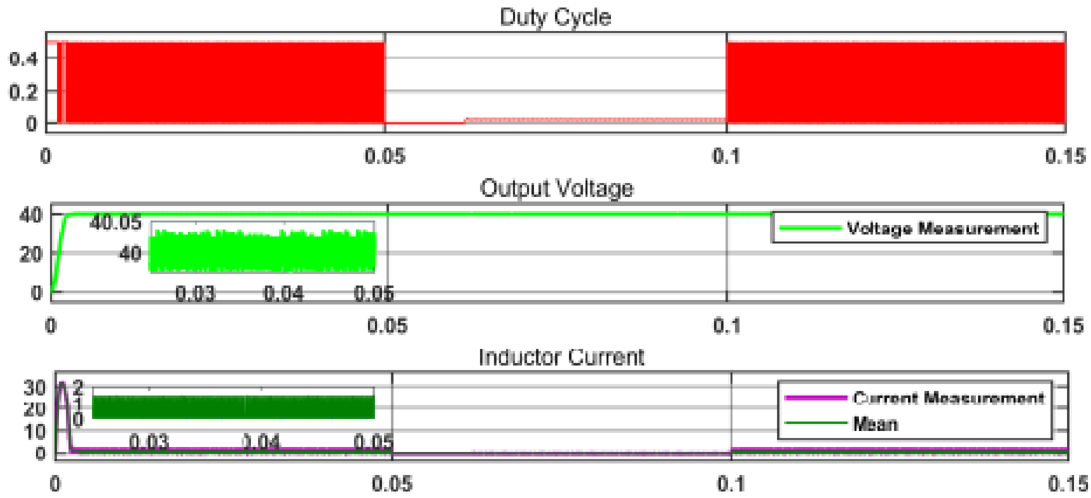


Fig. 8. Duty cycle, output voltage, inductor current of boost converter with fuzzy logic controller and variable load

4. COMPARISON RESULTS

For comparative purposes, the fuzzy logic controller result that depicted in Fig. 8 has been implemented to compare with the other working proposals, for full and half load with sampling time .05 sec. It is obvious that the proposed controller performs better in term of tracking load changing with a longer settling time of 0.025 sec. Fuzzy controller output is roughly equivalent to the PIDSMC's output, as settling time has fluctuation in both of them. Performance Analysis of LSMC exhibited free of chattering issues which is very important in power systems. Although LSMC exhibit a much longer rising time than PIDSMC by approximately 20ms in transient state, yet it showed very smooth response in a steady state voltage with almost zero chattering. This virtue might be very wanted in special electronic devices where chattering in supplied voltage is not tolerated.

5. CONCLUSIONS

A comparative study of two types of sliding mode control PIDSMC and LSMC have been investigated in this work beside an additional comparison of fuzzy logic controller. With PIDSMC, the output voltage regulated in a settling time (0.01 sec.) and little delay, while still suffering from the phenomenon of chattering, similar to that of the fuzzy logic controller. Although the settling time in case of LSMC (.025 sec.), is longer than the settling time when using PIDSMC, but on the other hand, obtaining a constant output voltage free of chattering. This is an important feature in the applications of the DC-DC convertors and power systems in general. Moreover, it has been shown robust control for variable load. Due to its nonlinear control and the ability to compensate the converter's nonlinearity because of internal uncertainty and external disturbances, the LSMC has a hopeful future in the application of DC-DC convertors. Also there is relatively less complexity associate with nonlinear mathematical analysis for implementation.

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