On two control approaches for the output voltage regulation of a boost converter

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Abstract—This paper deals with the comparison between two proposed control strategies for a DC-DC boost converter. The first control is a classical Sliding Mode Control (SMC) and the second one is a distance based Fuzzy Sliding Mode Control (FSMC). The SMC is an analytical control approach based on the boost mathematical model. However, the FSMC is a non-conventional control approach which does not need the controlled system mathematical model. It needs only the measures of the output voltage to perform the control signal. The obtained simulation results show that the two proposed control methods are robust for the case of load resistance and the input voltage variations. However, the proposed FSMC gives a better step voltage response than the one obtained by the SMC.

Keywords—Boost DC-DC converter, Sliding Mode Control (SMC), Fuzzy Sliding Mode Control (FSMC), Robustness.

I. INTRODUCTION

S WITCHED mode DC-DC converters are electronic circuits which convert a voltage from one level to another. Especially DC-DC Boost converters deliver a DC output voltage greater than the DC input one. Switched converters are considered to be the most advantageous supply tools for feeding some electronic systems in comparison with linear power supplies which are inefficient as they convert the dropped voltage into heat dissipation. As all the DC-DC converters, Boost converters are designed to work in open-loop mode. However, these kind of converters are non linear. This non-linearity is due to the switch and the converter component characteristics.

For some applications, the Boost converters must provide a regulated output voltage with low ripple rate. In addition, the converter must be robust against load or input voltage variations and converter parametric uncertainties. Thus, for such case the regulation of the output voltage must be performed in a closed loop control mode.

For this purpose, several control methods have been proposed, the first techniques that had been used are PI-type controllers [1]. The application of such control needs the linearization of the boost averaged mathematical model around an operating point. However, the linear models present some limitations because they badly represent the studied system which is nonlinear. For this reason, nonlinear control methods have been designed [2]-[6].

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Sliding Mode Control (SMC) is a non-linear control technique derived from variable structure control system theory and developed by Vladim UTKIN [7]. Such control solution has several advantages such as simple implementation, robustness and good dynamic response. Moreover, such control complies with the non-linear characteristic of the switch mode power supplies [8]. Although, the drawback of SMC is the chattering phenomena. To overcome the chattering problem SMC was extended to a Fuzzy Sliding Mode Control (FSMC).

Traditional SMC in which the use of HM leads to switch frequency variation as well as we have changes in the sliding surface S. In our case, fixed frequency PWM technique is used.

In [9] the authors show that the switching action is a composition of two isolated components: a continuous switching action produces the low frequency and a discontinuous switching action produces the high frequency. The high frequency is often filtered out by the output filter capacitor. For this reason we can consider only the continuous switching action and this is known as the equivalent control [9]-[11].

Fuzzy Logic Control is a non-conventional and robust control law. It is suitable for nonlinear or complex systems characterized by parametric fluctuation or uncertainties. SMC was extended to Fuzzy Sliding Mode Control (FSMC) in order to give more robustness and to overcome the problem of the chattering phenomena. The advantage of the FSMC is that it is not directly related to a mathematical model of the controlled systems as the SMC.

This paper aims to compare between SMC and FSMC of a Boost converter. It is organized as follows. Section 2 presents the studied Boost converter averaged non-linear model. Then, a classical SMC solution is presented in section 3. The proposed FSMC is described in section 4. Finally, the simulation results, obtained by application of the SMC and the FSMC are given and discussed in section 5.

II. BOOST CONVERTER MODELING

The Boost DC-DC converter, called also step-up converter, is a switching converter that produces an output voltage greater than its input voltage. When the switch S_w is closed (on state), the diode D is on inverse polarization, so isolating the output

from the input stage. The current i_L through the inductor L increases. When the switch S_w is open (off state), the diode is directly polarized and the only path to the inductor current is through the diode D, the capacitor C and the load R. Therefore, the inductor discharges its energy to the load.
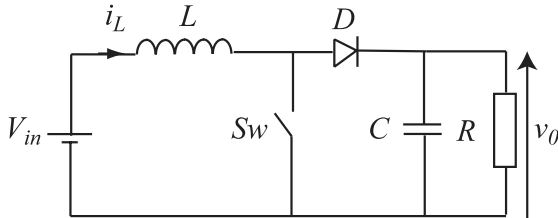

Fig. 1.   Structure of the studied Boost dc-dc converter

So, the studied converter has two working topologies corresponding to its switch states. The first topology, presented by the figure 2, corresponds to the on state of the switch.

The dynamical equations of the converter are given, for the first topology by the following equations:

$$\begin{cases} \frac{di_L}{dt} & = & \frac{V_{in}}{L} \\ \frac{dv_0}{dt} & = & -\frac{v_0}{RC} \end{cases} \tag{1}$$
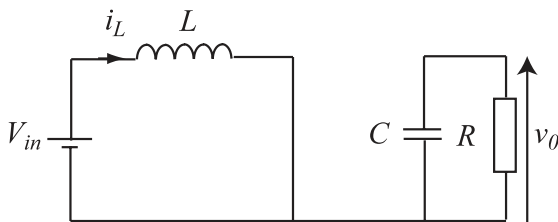

Fig. 2.   Equivalent circuit of the Boost converter (switch on)

The second topology, presented by the figure 3, corresponds to the off state of the switch. For this case, the diode conducts, and the dynamical equations of the converter are expressed as follows:

$$\begin{cases} \frac{di_L}{dt} & = & \frac{V_{in}}{L} - \frac{V_0}{L} \\ \frac{dv_0}{dt} & = & \frac{i_L}{C} - \frac{v_0}{RC} \end{cases} \tag{2}$$
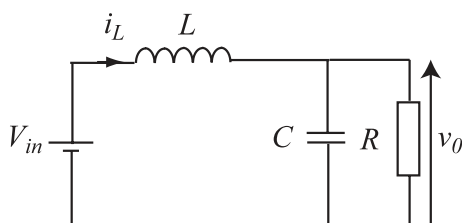

Fig. 3.   Equivalent circuit of the Boost converter (switch off)

The choice of the following state vector $x = \begin{bmatrix} i_L \\ v_0 \end{bmatrix}$ allows the state-space representation for mode 1 by:

$$\begin{cases} \dot{x}_1 & = & A_1 x + B_1 u \\ v_0 & = & C_1 x \end{cases} \tag{3}$$

Where:

$$A_1 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}, B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, C_1 = [0 \; 1] \text{ et } u = V_{in}$$

and the state-space representation for mode 2 by,

$$\begin{cases} \dot{x}_2 & = & A_2 x + B_2 u \\ v_0 & = & C_2 x \end{cases} \tag{4}$$

Where:

$$A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, B_2 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, C_2 = [0 \; 1] \text{ et } u = V_{in}.$$

The state-space averaging method replaces the state-equations by a single state-space description which represents approximately the behaviour of the circuit across the whole period.

So the combination of state-space representation of mode 1 (on mode) and mode 2 (off mode) described respectively equations by (3) and (4) induces the following nonlinear state space representation:

$$\begin{cases} \dot{x} = [dA_1 + (1 - d)A_2]x + [dB_1 + (1 - d)B_2]V_{in} \\ v_0 = [dC_1 + (1 - d)C_2]x \end{cases} \tag{5}$$

where d takes 1 for the ON state of the switch and 0 for the OFF state. So the boost converter is modeled as follows:

$$\begin{cases} \dot{x} = \begin{bmatrix} 0 & -\frac{1-d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} x + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} V_{in} \\ v_0 = [0 \; 1]x \end{cases} \tag{6}$$

III. PROPOSED SLIDING MODE CONTROLLER

The SMC is a nonlinear control approach which complies with the nonlinear characteristic of the boost converter. Such control technique is robust and it is characterized by a good dynamical response.

Let us consider the following sliding surface S:

$$S = Ke + \dot{e} \tag{7}$$

where e is the output voltage error defined as follows:

$$e = v_0^\star - v_0 \tag{8}$$

K is chosen so that it guarantees a good regulation of the output voltage with a near zero steady-state error and minimum of overshoot. The control signal is pulse width modulated. Thus only the equivalent control component has

to be determined and applied to the switch. When the system is on the sliding surface, we have:

$$S = 0 \qquad (9)$$

And :

$$\dot{S} = 0 \qquad (10)$$

By considering the mathematical model of the DC-DC Boost converter, at the steady state the variation of the surface can be expressed by the following expression :

$$\dot{S} = -K\dot{v}_0 - \ddot{v}_0 \qquad (11)$$

From equations 6, 10 and 11 we can deduce that:

$$-K\dot{v}_0 + \frac{\dot{v}_0}{RC} = \frac{1-d}{C}\dot{i}_L \qquad (12)$$

Then, from the state representation we can write:

$$\dot{v}_0(\frac{1}{RC} - K) = \frac{1-d}{C}(\frac{d-1}{L}v_0 + \frac{v_{in}}{L}) \qquad (13)$$

Finally, the equivalent control is expressed as follows:

$$d = 1 - \frac{v_{in} + \sqrt{v_{in}^2 + \frac{4KL}{R}(CRK-1)(v_0^\star - v_0)}}{2v_0} \qquad (14)$$

The figure 4 presents the structure of the SMC principle of the described SMC.

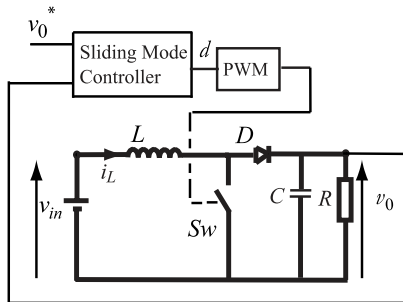Fig. 4. The considered SMC

IV. PROPOSED FUZZY SLIDING MODE CONTROLLER

Fuzzy logic control is a nonlinear and robust control approach. It is suitable for nonlinear or complex systems characterized by parametric uncertainties and fluctuations. The extension of the SMC into a FSMC aims to improve the robustness of the controlled systems and the elimination of the chattering phenomenon. In the following we propose to apply and to adapt the method proposed by R. PALM in [12] to the studied Boost converter.

The sliding surface defined by the equation 3 can be expressed as follows:

$$S = EY^T \qquad (15)$$

Where $E = [e \quad \dot{e}]$ and $Y = [K \quad 1]$. The distance between the trajectory error and the sliding surface d_{sn} is defined as follows [13]-[15]:

$$d_{sn} = \frac{\dot{e}_p + Ke_p}{\sqrt{1 + K^2}} \qquad (16)$$

d_{sn} is the normal distance between the point $P(e_p, \dot{e}_p)$ and the sliding surface (switching line). Such distance is illustrated graphically in figure 5 for an arbitrary point $P(e_p, \dot{e}_p)$.
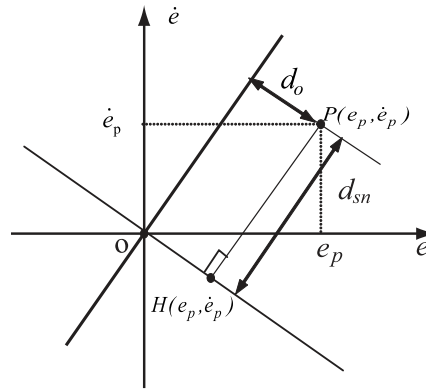

Fig. 5. Distances d_{sn} and d

Let $H(e_p, \dot{e}_p)$ be the intersection point of the switching line and its perpendicular passing through the point $P(e_p, \dot{e}_p)$. d_0 is defined as the distance between the point $H(e_p, \dot{e}_p)$ and the origin point O. The distance d_0 is expressed as follows :

$$d_0 = \sqrt{|E|^2 - d_{sn}^2} \qquad (17)$$

The proposed fuzzy sliding mode controller has as inputs the two distances d_{sn} and d_0. The output signal is the control increment $\Delta d(K)$ which is used to update the control signal defined as follows :

$$d(K) = \Delta d(K) + d(K-1) \qquad (18)$$

Trapezoidal and triangular membership functions, denoted by N (Negative), Z (Zero) and P (Positive), were used for d_{sn}. The same shape of membership functions denoted by Z (Zero), PS (Positive small) and PB (Positive Big) are used for d_0.

d_{sn} and d_0 membership functions are presented respectively in figures 6 and 7 in the normalized domain $[-1 \quad 1]$ for d_{sn} and $[0 \quad 1]$ for d_0.
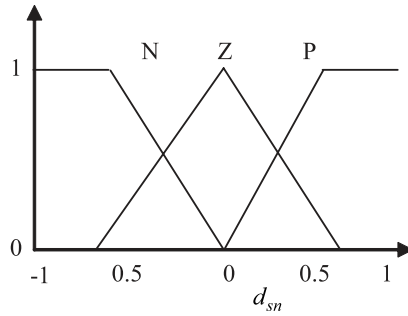
Fig. 6. d_{sn} membership functions

For the output signal of the proposed FSMC, fives triangular membership functions, denoted by NB (Negative Big), NM (Negative Middle), Z (Zero), PM (Positive Middle), PB (Positive Big) are used for the output signal Δd (8). The rule base is given by the table I.
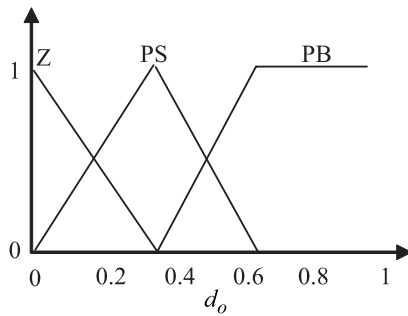

Fig. 7. d_0 membership functions

TABLE I
RULE BASE OF THE PROPOSED FSMC

		d_{sn}		
		N	Z	P
	Z	PS	Z	NS
d_0	PS	PB	PS	NB
	PB	PB	NS	NB

The proposed control diagram is presented in figure 9 where K_1 and K_2 are the input scaling factor and K_3 is the output one.
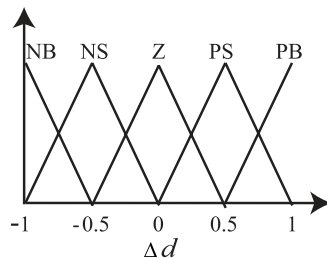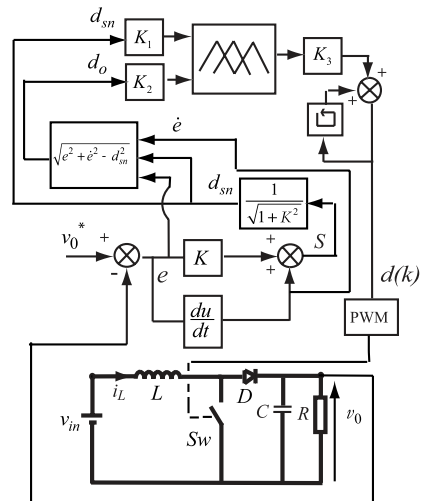

Fig. 8. Δd membership functions

Fig. 9. Principle of the proposed FSMC

V. SIMULATION RESULTS

The proposed FSMC and SMC were tested by simulation. The electrical parameters of the studied Boost converter are given in table II.

TABLE II
STUDIED BOOST CONVERTER PARAMETERS

Parameters	Values
v_{in}	$20V$
C	$22.10^{-6}F$
L	$3.10^{-3}H$
R	15Ω
Switching Frequency	$100.10^3 Hz$

The classical SMC, described above, was compared to the proposed FSMC. Figures 10 and 11 give the simulated step responses of the studied boost converter for $40V$ reference voltage. From the obtained results the two figures we can conclude that the dynamical behavior of the transient state voltage response obtained by the FSMC is better than the one obtained by SMC. Indeed, the overshoot obtained by the SMC is 10%. It is reduced to 2% by application of the FSMC.
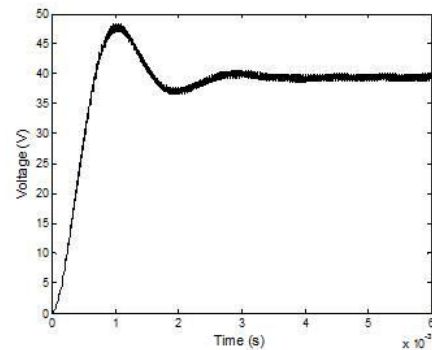

Fig. 10. Step voltage responses of the boost converter by application of the SMC
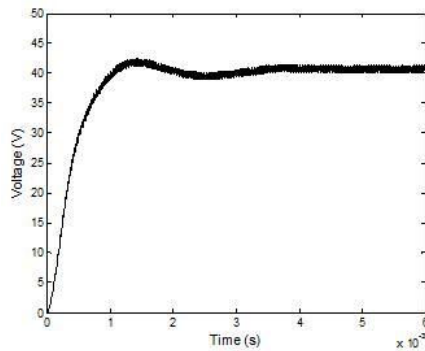
Fig. 11. Step voltage responses of the boost converter by application of the FSMC

In order to test the robustness of the two control methods, simulations are given for the case of the load and the input voltage variations. Figures 12 and 13 present the variation of the output voltage under changes in load resistance from 15Ω to 12.5Ω at 0.01s. We can notice that the two controllers reject such perturbation.
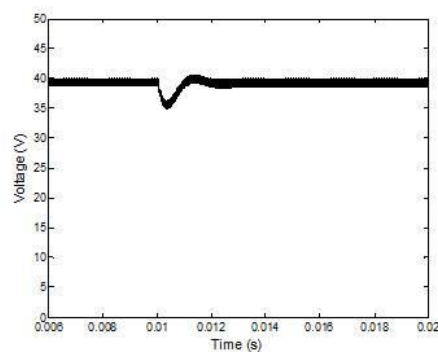

Fig. 12. Robustness test of the SMC for the variation of the load resistance
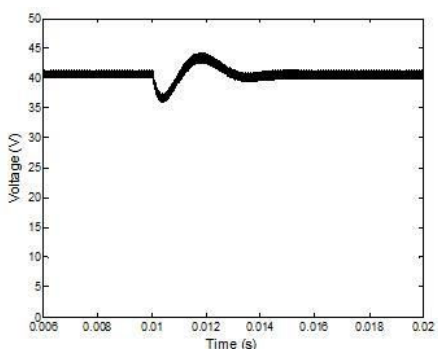

Fig. 13. Robustness test of the FSMC for the variation of the load resistance

From figures 14 to 16 we test the Boost DC-DC converter when the input voltage varies. Figure 14 illustrates the variation of the input voltage from 20V to 18V. We can notice in figure 15 and in figure 16 that the two controllers reject also the input voltage variation.
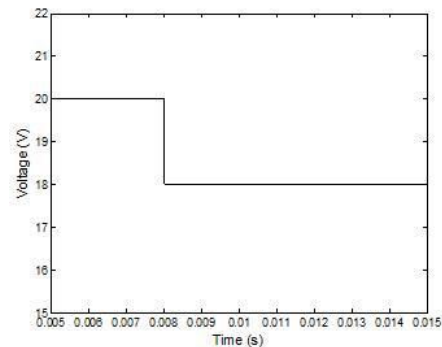

Fig. 14. Variation of the input voltage from 20V A to 18V
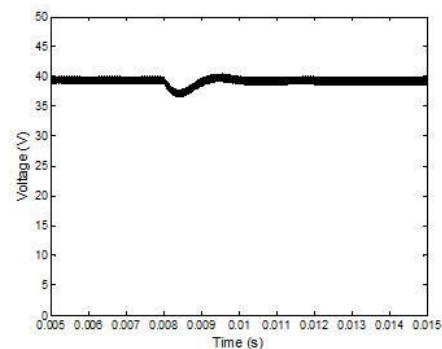

Fig. 15. Robustness test of the SMC for the variation of the input voltage

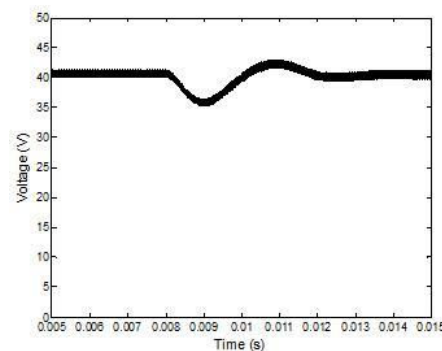Fig. 16. Robustness test of the FSMC for the variation of the input voltage

VI. CONCLUSION

In this paper, we propose two controllers to regulate the output voltage of a DC-DC Boost converter based on SMC and FSMC. The determination of the control signal of the SMC is based on an analytical approach exploiting the dynamical model of the studied converter. However, the FSMC does not need any model. As the SMC, the FSMC

complies with the nonlinear characteristic of the studied converter. Although, it offers better performances in terms of overshoot limitation of the voltage step response than the SMC. The robustness test results for the cases of the load and input voltage variations prove that the SMC and FSMC give similar and good results.

NOMENCLATURE

v_{in}	:	input voltage
$v_0^{\star}$	:	reference voltage
C	:	capacitance
L	:	inductance
R	:	load resistance
v_0	:	output voltage
i_L	:	current inductance
d	:	equivalent control signal

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