International Journal of Sciences and Techniques of Automatic control & computer engineering
IJ-STA, Volume 14, N°1, September 2022, pp 2162–2167.

Effect of parasites in the boost converter sliding mode controller

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***Abstract*—This paper designe a novel sliding mode controller (SMCs) for DC-DC boost converter while considering parasites and modelling uncertainties. It considers detailed modelling of the boost and introduces an appropriate control method while analysing the system's real behaviour. Anonlinear sliding surface is designed, and the stability analysis is investigated by the Lyapunov approach. The proposed controller enables to reduce of the chattering and the output voltage error. Experiments have been performed to assess the real behaviour of the system while considering different scenarios. The obtained results show a superiority of the proposed results.**

***Index Terms*—imperfect DC-DC boost converter, nonlinear sliding surface**

I. Introduction

DC-DC boost converters are potentially enabling renewable energy resources integration and smoothing the connection andcombination of multi-energy resources. One of the main applications is stabilising the output voltage when connected to arenewable energy source [1]. For instance, DC-DC boost converters are widely deployed insolar and energystorage systems. These systems exhibit a variable voltage operating range, and the use of DC-DC, in this case, is pivotal in unlocking these energy systems' full potential and ensuring an efficient deployment.

It is worthnoting thatDC-DC boost converters are nonlinear systems. The design of a controller, in this case, is tricky and complex. Moreover, these systems have minimum phase characteristics which add more complexity to controller design and stability analysis.

In the recent literature, many efforts have been devoted to solving control issues for such DC-DC boost converters. A parallel damped passivity-based control approach has been designed in [2]. The authorsin [3-4-5] have used the backstepping approach for designing a control method. The deployment of sliding mode control and its theory has also beeninvestigated in many research works[6-7-8], and itwas pointed outhow chattering problems can limit SMCs control performances.

Usually, linear sliding surfaces are designed;however, the analysis of nonlinear sliding surfaces is attracting growing interest. Recent previous works [9-10] demonstrate that the designed SMC with a nonlinear sliding surface could minimize chattering [11-12] and solve the non-minimum phase control issue.

A real implementation of such a control approach has been initiated in a few recent research works. In real cases and due to the modelling and operating condition of the systems, the boost converter generates an output voltage error [13] which can be explained by the discontinuous signum function [14] or by the imperfections of modelling [15]. To overcome the "sign" effect, an integral action was proposed in [16]. However, this issue is still impacting the control performances, mainly tracking and chattering.

In an effort to address the above SMC limitations for DC-DC boost converter control application, we propose in this paper an exact modelling of an imperfect boost by adding the associated parasites and designing an appropriate control method while analysing the real system behavior.

This paper is structured in this way—section 2 is dedicated to the modelling of an imperfect boost converter. Then, the designed SMC is detailed in section 3.The main objectives are 1) reduced chattering, 2) minimised output voltage error. Experimental comparisonsbetween the perfect and the imperfect casearepresented in section 4. Section 5 concludes this paper and proposes futur lines of research.

II. Modelling of an Imperfect Boost converter

This converter is subject to many parasitic elements that can impact the modelling accuracy and, thus, the control performances. The main parasite elements are the ON state MOSFET resistance, the inductor effective series resistance, the forward diode resistance, and the forward voltage diode. Thus this paper suggests considering the latter elements in a detailed modelling approach.

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This paper was recommended for publication in revised form by the Editor Staff.
Edition: CPU of Tunis, Tunisia, ISSN: 1737-7749

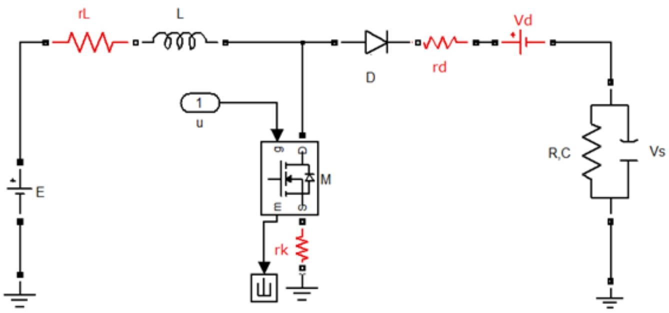


Fig. 1. Imperfect boost converter

Fig.1 presents the imperfect boost set-up, where u is the duty cycle. Eand V_s are, respectively, the input and the output voltage. D is the diode and M (MOSFET) is the active switch. R, C, L are the resistor,the filter capacitor, the inductor. The parasitic elements are: r_k (the ON state MOSFET resistance), and r_L (the inductor effective series resistance) V_d (the forward voltage of the diode) and r_d (the forward diode resistance).

Eq (1) describe the average model of this converter:

$$\begin{cases} L\dfrac{dx_1(t)}{dt} = -(1-u(t))x_2(t) + E - r_L x_1(t) - (1-u(t))r_d x_1(t) \\ \qquad - r_k u(t) - (1-u(t))V_d \\ C\dfrac{dx_2(t)}{dt} = (1-u(t))x_1(t) - \dfrac{x_2(t)}{R} \end{cases} \qquad (1)$$

where x_1 , x_2 are respectively the average values of the input current and the output voltage.

The equilibrium values of x_1 and x_2 satisfy the following relations:

$$X_{2e} = \frac{(E-V_d(1-U))(1-U)}{\dfrac{r_L + Ur_k + (1-U)r_d + R(1-U)^2}{R}} \qquad (2)$$

$$X_{1e} = \frac{E-V_d(1-U)}{r_L + Ur_k + (1-U)r_d + R(1-U)^2} \qquad (3)$$

$$X_{1e} = \frac{X_{2e}}{R(1-U)} \qquad (4)$$

where $X_{1r} = x_{1\infty}$ and $X_{2r} = x_{2\infty}$ are resectively the referencs values of x_1 and x_2 and $u_\infty = U, (0 < U < 1)$.

III. THE DESIGNED SLIDING MODE CONTROLLER

As discussed in the introduction section, we propose a nonlinear surface-based SMC controller for stabilising and enhancing the control performance of the boost.

The control law is designed in Theorem 1. The stability analysis is described in the following parts of this section.

A. *Sliding surface*

To start our analysis, we suggest this nonlinear sliding surface:

$$S(t) = K_1(\dot{x}_1(t) - \dot{X}_{1r}) + K_2(x_1(t)^2 - X_{1r}^2) \qquad (5)$$

After replacing $\dot{x}_1$ and $\dot{x}_2$ by their expressions presented in (1), $S(t)$ is rewritten by (6):

$$S(t) = \frac{K_1}{L}(-(1-u(t))x_2(t) - r_L x_1(t) - (1-u(t))r_d x_1(t) + E \\ -r_k u(t) - (1-u(t))V_d) + K_2(x_1(t)^2 - X_{1r}^2) \qquad (6)$$

B. *The proposed control law*

Assumption 1. The sliding surface first derivative is assumed to have the reaching law giving by (7):

$$\dot{S}(t) = -\eta(S(t) + \omega \text{sign} S(t)) \qquad (7)$$

where $\eta > 0$, $\omega > 0$. The latter conditions are designed to confirm the SMC's existence condition ($S(t)\dot{S}(t) < 0$).

Remark 1. In order to reduce chattering, small values of ω are being requested. However, small values of η slow down the reaching time and an important value for η , can increase the reach rate once the state is far of the sliding surface.

The novel SMC law is given by Theorem1:

Theorem 1. Considering assumption 1, the dynamic of the designed SMC of the imperfect boost converter presented by (1) is:

$$\dot{u} = \frac{L}{K_1(x_2 - r_k + V_d + r_d x_1)}\left(\frac{K_1(1-u)}{L}\dot{x}_2 + \frac{K_1 r_L \dot{x}_1}{L} \\ + \frac{K_1 r_d \dot{x}_1(1-u)}{L} - 2K_2 x_1 \dot{x}_1 - \eta(S + \omega \text{sign} S)\right) \qquad (1)$$

To establish the asymptotic stability of the system, the controller gains are designed as: $K_1 > 0$, $K_2 > 0$ $\eta > 0$, $\omega > 0$

Proof:

In the first step, we compute the sliding surface derivative:

$$\dot{S} = \frac{K_1}{L}(-(1-u)\dot{x}_2 + \dot{u}x_2 - r_L\dot{x}_1 - (1-u)r_d\dot{x}_1 \\ -r_k\dot{u} + \dot{u}V_d) + 2K_2 x_1 \dot{x}_1 \qquad (9)$$

(9) and (7) are the same quantity; we deduce thenthat we have:

$$\frac{K_1}{L}(-(1-u)\dot{x}_2 + \dot{u}x_2 - r_L\dot{x}_1 - (1-u)r_d\dot{x}_1 - r_k\dot{u} + \dot{u}V_d) \\ +2K_2 x_1 \dot{x}_1 = -\eta(S + \omega \text{sign} S))$$

As a consequence, we conclude the following dynamic behaviour of u:

$$\dot{u} = \frac{L}{K_1(x_2 - r_k + V_d + r_d x_1)}\left(\frac{K_1(1-u)}{L}\dot{x}_2 + \frac{K_1 r_L \dot{x}_1}{L} + \frac{K_1 r_d \dot{x}_1(1-u)}{L} - 2K_2 x_1 \dot{x}_1 - \eta(S + \omega \operatorname{sign} S)\right)$$

We verify the system stability if its dynamic in sliding regime tends to the desired value .

Eq (10) gives the Lyapunov function :

$$V = \frac{1}{2}e_1^2 \quad (10)$$

With : $e_1 = x_1 - X_{1r}$

$\dot{V} = e_1\dot{e}_1 = e_1\dot{x}_1$

$\dot{x}_1$ is deduced from $S(t) = 0$:

$$\dot{x}_1 = -\frac{K_2}{K_1}(x_1^2 - X_{1r}{}^2)$$

$$\dot{V} = -\frac{K_2}{K_1}(x_1 - X_{1r})^2(x_1 + X_{1r}) \quad (11)$$

The stability of $x_1(t)$ is established if K_1 and K_2 are positive.

So, $x_1(t) \to X_{1r}$ and $\dot{x}_1(t) \to 0$ then $x_2(t) \to X_{2r}$.

Consenqently, the stability of $x_2(t)$ is verified.

IV. EXPERIMENTAL RESULTS

Experiments are performed to analyse the designed control approach's performance for the boost. Three main scenarios are considered for a closed-loop approach to analyse the proposed control approach's robustness and superiority. Fig.2 describes the hardware used for the real-time implementation and the boost converter prototype.

The controllers have been implemented, with a switching frequency $F = 5\ kHz$,through Dspace DS1104.

The components of the boost converter and controllers gains were:

- $R = 30\Omega, E = 15\ V, C = 100\mu F, L = 10mH$;
- $r_L = 0.0705\Omega,\ r_d = 0.107\Omega, r_k = 0.2\Omega,\ V_d = 0.85V$;
- $u(0) = 0.1, x_1(0) = 0.5A, x_2(0) = 20V$;

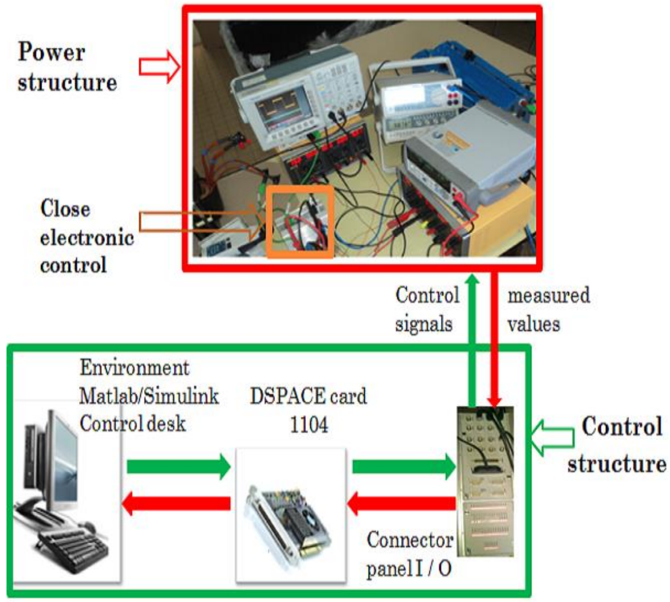
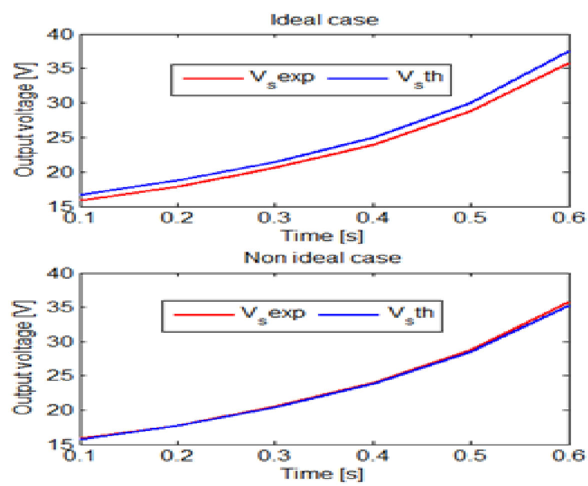


Fig. 2. Schematic of the complete prototype

A. *Experiments in open loop*

By introducing the boost parasitic elements, we can reduce the gap between theoretical values and experimental values seen in the perfect case (Fig. 3).



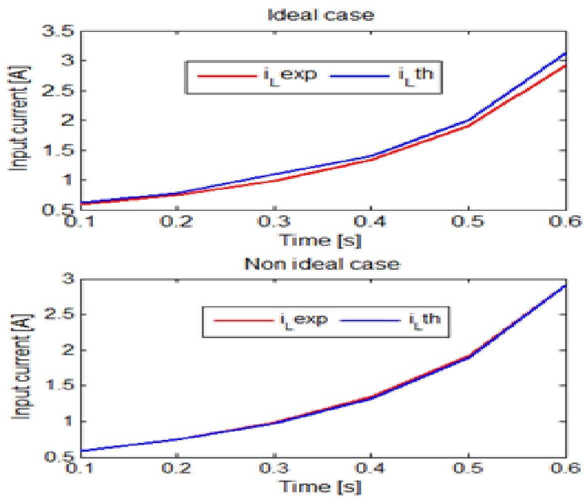


Fig.3. Experiment results in open loop

B. Experiments in closed loop

Three scenarios have been assessed to validate the effectiveness and robustness of the developed approach:

- test 1: variation of current reference;
- test 2: variation of resistance;
- test 3: variation of input voltage.

The parameters of the controller for both non-ideal and ideal cases are described as follows:

- The imperfect case:
  $\eta = 100, \omega = 0.0001, K_1 = 0.001, K_2 = 0.2$
- The perfectt case:
  $\eta = 100, \omega = 0.0001, K_1 = 0.0048, K_2 = 0.4$

Test 1:

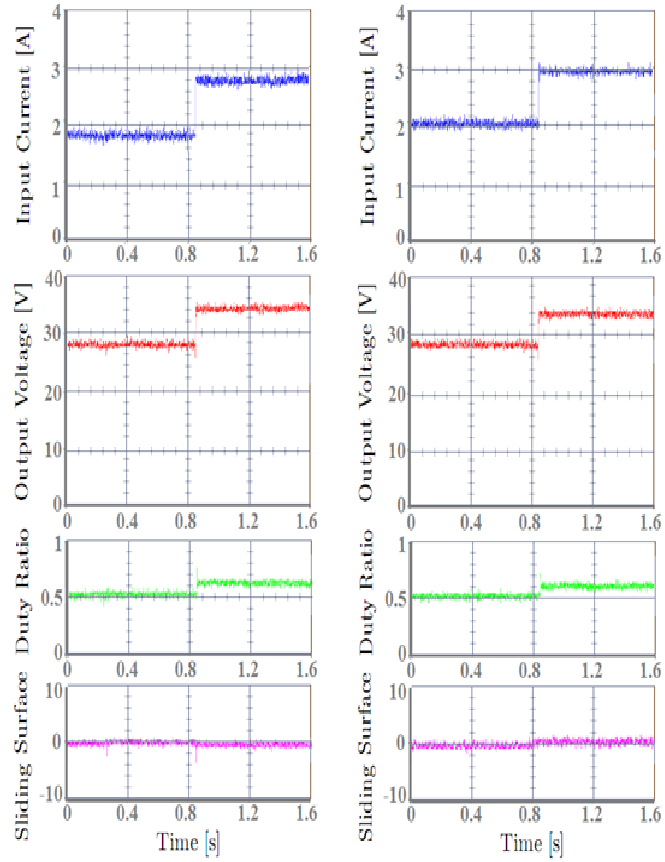
In the first scenario, we propose to change the current reference value from $2A$ to $3A$ at $t = 0.8s$.

Theoretical values of X_{2r}andUare presented by Table 1.

Table 1. Theoretical values of X_{2r}andU

	without parasites		with parasites	
X_{1r}	X_{2r}	U	X_{2r}	U
2 A	30 V	0.5	29.22 V	0.51
3 A	36.74 V	0.6	35.6 V	0.61

The outputs of this experiment are presented in Fig.4. The input current, the output voltage, the duty cycle, and the sliding surface are presented for both ideal (without parasites) and non-ideal cases (with parasites). The analysis of the obtained results shows that both control laws can eliminate chattering. However, Fig. 4 (a) indicates that the designed controller applied to a perfect boost generates a state error due to the presence of parasitic elements. Thus, a good input current tracking see in Fig. 4 (b) through considering parasites.



(a) without parasites (b) with parasites

Fig.4. Experimental results with reference variation.

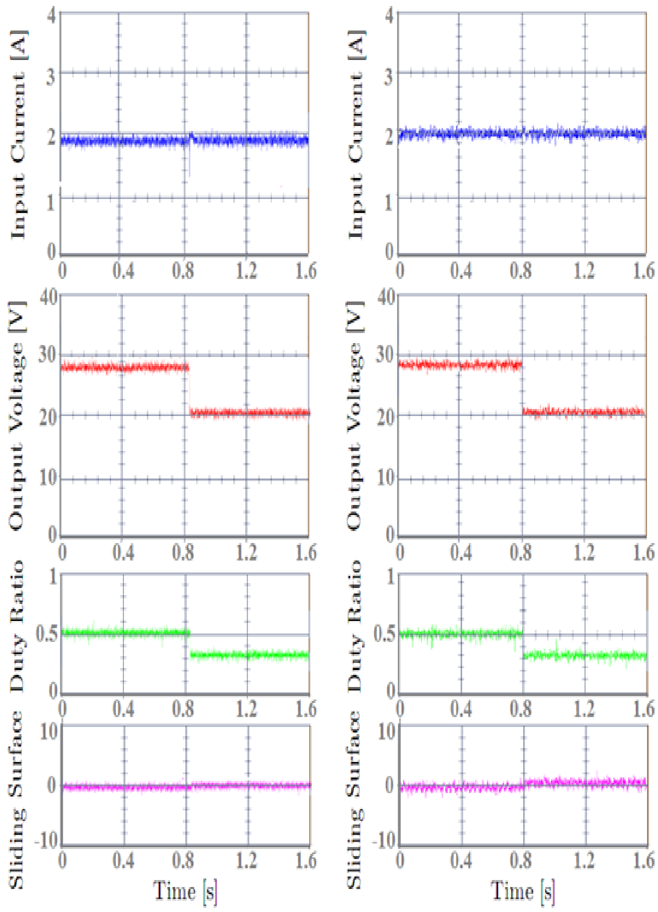
Test2:

In the second scenario, we propose an analysis of the robustness in case of a change in load resistance value.Thus, at $t = 0.8s$ a load resistor changes through a switch from $R = 30\Omega$ to $R = 15\Omega$ .X_{2r} and U are given by Table. 2.

Table 2. Theoretical values of X_{2r} and U

	without parasites		with parasites	
R	X_{2r}	c	X_{2r}	U
30 Ω	30 V	0.5	29.22 V	0.51
15 Ω	21.21V	0.6	20.6 V	0.31

Fig.5 exhibits that the imperfect boost converter controller is not sensitive to this variation. Nevertheless, the state error of x_1 and x_2 curves presented in the perfect case can affect the robustness of this control law. Thus, we deduce that the proposed control is robust to a load resistor variation.



(a) without parasites (b) with parasites

Fig.5. Experimental results with resistor variation.

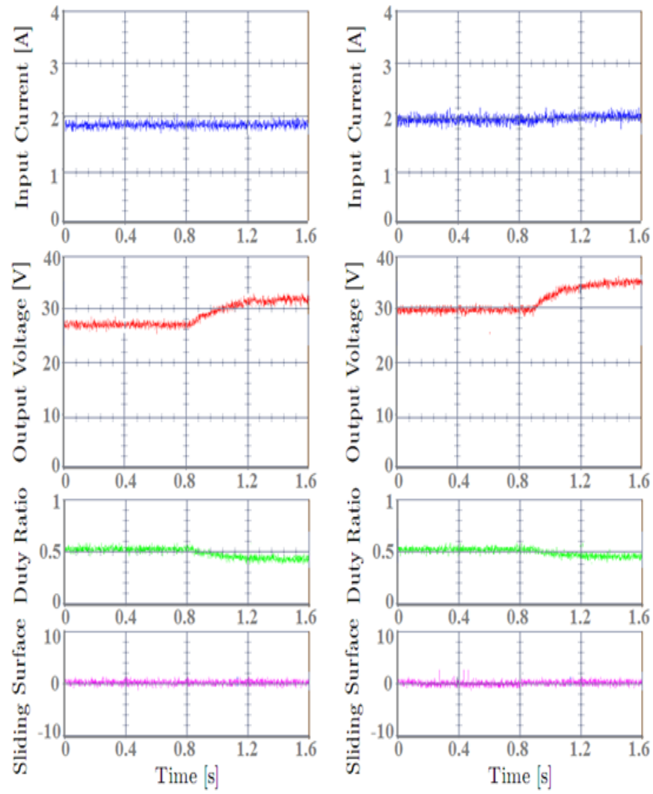
Test 3:

In the third scenario, the robustness and the performances of the controller are tested through a sudden variation at $t = 0.8s$ from $E = 15V$ to $E = 20V$. We took $R = 30\Omega$, $X_{1r} = 2A$, X_{2r} and U are given in Table. 3.

Table3. Theoretical values of X_{2r}andU

	without parasites		with parasites	
E	X_{2r}	U	X_{2r}	U
15 V	30	0.5	29.22 V	0.51
20 V	34.64	0.43	33.95 V	0.44

The analysis of the results described in Fig.6 shows that the output voltage state error is minimal and the input current is not sensitive to this variation in the perfect case. As a consequence, we can deduce that the parasitic elements have a bad influence on the robustnessunder input voltage variation of the real boost.



(a) without parasites (b) with parasites

Fig.6. Experimental results with input voltage variation.

V. Conclusion

This paper proposes an SMC control strategy for a DC/DC boost converter while considering the identification of detailed modelling and non-ideal parameters.An equivalent dynamic model has been described. A nonlinear surface has been designed and the stability analysis has been performed based on the Lyapunov stability theory. The nonlinear SMC controller's performances and robustness have been tested by assessing different experiment scenarios. The obtained results confirm the proposed approach's superiority and ability to deal with non-ideal real-case operating conditions. The comparison between the perfect case and the imperfect case shows that the developed approach with a nonlinear sliding surface decrease the error of the output voltage by considering parasites. In addition, we confirm its robustness with the reference, the load and the input voltage variations. A thorough analysis will be assessed in future works. Indeed, we plan to couple the proposed control law to an MPPT controller and ameliorate the performances of the energy conversion system solar energy from solar panels into actual electrical energy applied to a charge.

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