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COMPARISON BETWEEN NON LINEAR CONTROLLERS APPLIED TO A DC-DC BOOST CONVERTER

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Abstract. *The regulation problem of the DC-DC boost converter with Sliding Mode Controller (SMC) is a very challenging issue due to the non-minimum phase behavior and the chattering problem of SMCs. A new sliding mode controller is developed to deal with this behavior and at the same time aims at eliminating the chattering phenomenon. The effectiveness and the robustness of this controller are demonstrated by comparison with some controllers from the literature through computer simulations.*
Keywords: Regulation, DC-DC boost converter, Sliding mode controller, Non-minimum phase, Chattering phenomenon

1. **Introduction.** Robust nonlinear control applied to a DC-DC boost converter is one of the modern research areas in power electronics and in automatic control.

The non-minimum phase output voltage behavior makes the DC-DC boost converter one of complex systems. Therefore, the output voltage regulation is made indirectly through the input current regulation.

Many controllers are developed in order to deal with the non-minimum phase property. They usually provide a fast transient response and cope with the boost converter parameter variations. In [5, 25], the Parallel Damped Passivity Based Controller (PD-PBC) proved to achieve a fast response but at the same time was unable to maintain an acceptable robust performance bound under load variations. However, the Backstepping Controller (BC) in [4, 8, 15] proved to be robust. The comparison presented in [22] concludes that the BC is better than the PD-PBC. In [26], a synergetic control approach was applied to a boost converter and it was shown that in its simple version (with no additional integrator), the synergetic control is not really robust with respect to load variation. An additional integral term provides more robustness but unfortunately at the expense of an acceptable settling time. In [24], optimization techniques for a feedback controller design for DC-DC boost converter were applied and proved through simulation results that they were not robust to a load resistance variation.

Recently, Sliding mode controllers (SMCs) have attracted many researchers and are reported to be robust and to give rise to fast response. Their application to a wide variety of systems is due to the popularity among the control community. For instance, the sliding mode strategy has been used for stochastic systems [33, 34, 35], time delay systems [32, 38], switched system [30, 31] and Markovian jump systems [36, 39, 40].

Especially for a DC-DC converter, many sliding surface forms have been proposed in the literature, for example, the classic sliding mode controller (CSMC) with a classic sliding surface as in [8, 9], the generalized PI sliding mode controller (GPISMC) with a PI sliding surface as in [2, 3], the sliding mode controller based on extended linearization (SMCBEL) proposed in [10].

Unfortunately, they exhibit a chattering phenomenon which could lead to low control accuracy, high wear of moving mechanical parts and high heat losses in electrical power circuits [23]. Thus, many solutions have been proposed to overcome this problem such as combining SMC with other controllers such as Generalized PI SMC in [3], fuzzy SMC in [11], Backstepping SMC in [12]. However, these controllers are still not able to deal with the non-minimum phase behavior of the boost converter [17]. Another solution presented in [13, 14] involves a second order SMC by using the super twisting algorithm. The approach is able to reduce the chattering phenomenon but the choice of the super twisting parameters is still arbitrary. In [18], the double integral SMC was shown to have a good behavior compared to a simple integral SMC approach. The obtained results with a double integral SMC controller show a reduction of the chattering phenomenon which remains still unsatisfactory. In [21], an augmented sliding mode observer approach was proposed and it succeeds to achieve less chattering phenomenon compared to the integral sliding mode proposed in [20].

A sliding mode controller with a new non linear sliding surface (PSMC) proposed in [7], has the merit to address both issues, that is, the non-minimum phase behavior as well as the chattering phenomenon.

In order to test the effectiveness and the robustness of the proposed controller, a comparison with other controllers (PD-PBC, BC, CSMC, GPISMC and SMCBEL) is presented in this paper. The issue of load resistor variation is also addressed.

It is worth noting that other controllers based especially on the fuzzy logic have addressed in particular the chattering phenomenon, with less or more success, see for instance [16, 19, 28] and the reference therein. These kinds of controllers are not considered in this work.

Moreover, switched system has been adopted as a possible description of the behavior of a DC-DC converter. For instance, a description as a switched system is given in [29] where the control law is the switching sequence allowing the DC-DC converter to switch from a mode to another. The DC-DC converter has in fact two modes as described in Section 2.

The paper is organized as follows. Section 2 presents the boost converter model. Section 3 is devoted to the design of the proposed sliding mode controller. A comparison between the PSMC, the PDPBC and the BC is given in Section 4. Section 5 is reserved to a comparison between the PSMC and the CSMC, the GPISMC and the SMCBEL and Section 6 contains the conclusion.

2. **Boost Converter Model.** The boost converter as shown in Figure 1 is made of:

- A DC voltage source E from photovoltaic panels that power the circuit.
- A MOSFET which is a field effect transistor and for which the control is a voltage. It requires only a low energy (insulated gate) and its drive current is almost zero

(pulse). The MOSFET is periodically conductive with a duty cycle at a frequency F.

- Passive components such as reactive inductance L and capacitance C.
- A resistor R which represents the load of the converter.

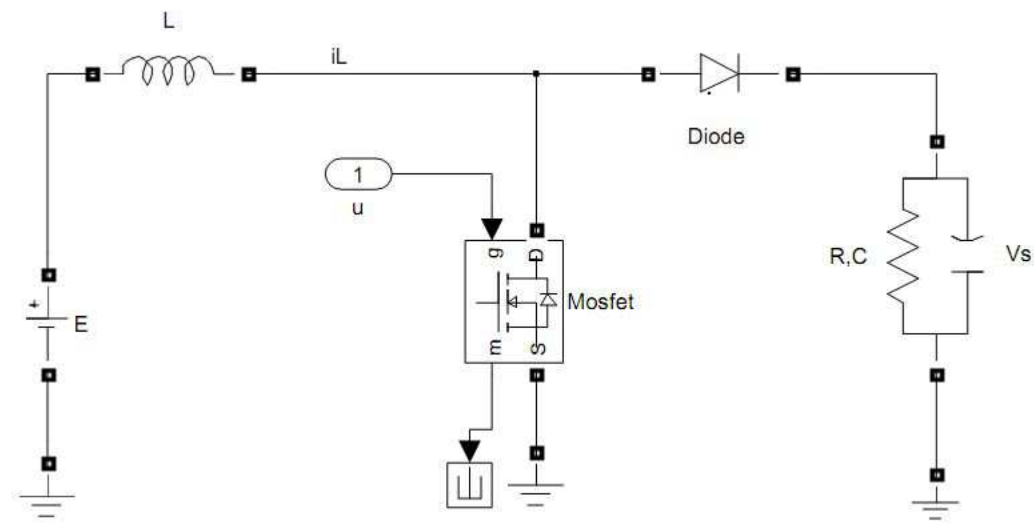

FIGURE 1. Boost converter

The state model of the Boost converter is given by the following equations:

$$\begin{aligned} L\frac{di_L(t)}{dt} &= -(1-\mu(t))V_s(t) + E \\ C\frac{dV_s(t)}{dt} &= (1-\mu(t))i_L(t) - \frac{V_s(t)}{R} \end{aligned} \tag{1}$$

where i_L is the input current and V_s is the output voltage.

The average Boost converter model is defined by formally replacing the discontinuous control function μ in (1) by a continuous piecewise smooth function u [1]

$$\begin{aligned} L\frac{dx_1(t)}{dt} &= -(1-u(t))x_2(t) + E \\ C\frac{dx_2(t)}{dt} &= (1-u(t))x_1(t) - \frac{x_2(t)}{R} \end{aligned} \tag{2}$$

where x_1 is the average value of the input current and x_2 is the average value of the output voltage.

Letting X_{1r} be a constant input current reference value, the equilibrium values of the state components $x_1(t)$ and $x_2(t)$ are then given by $x_{1\infty} = X_{1r}$ and $x_{2\infty} = X_{2r}$. The control $u(t)$ tends to $u_\infty = U$, with $0 < U < 1$. As a consequence in the equilibrium point, we have the following equations:

$$X_{1r} = \frac{E}{R(1-U)^2} \tag{3}$$

$$X_{2r} = \frac{E}{1-U} \tag{4}$$

which implies the constraint $X_{2r} = \sqrt{X_{1r}RE}$.

3. **The Proposed Sliding Mode Controller.** The proposed non linear sliding surface is given by the following expression:

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

It can be rewritten by replacing $\dot{x}_1$ and $\dot{x}_2$ by their expressions given in (2).

$$S_{NL}(t) = -K_1(1-u(t))\frac{x_2(t)}{L} + K_1\frac{E}{L} + K_2(x_1(t)^2 - X_{1r}^2). \tag{6}$$

3.1. **Existence condition.** The existence condition of sliding mode implies that $S_{NL}(t) \to 0$ and $\dot{S}_{NL}(t) \to 0$ when t tends to infinity, which means that the dynamic of the system will stay into the sliding surface. The existence condition of the sliding mode is

$$S_{NL}(t)\dot{S}_{NL}(t) < 0. \tag{7}$$

The reaching law is selected as follows:

$$\dot{S}_{NL}(t) = -\eta(S_{NL}(t) + \omega \text{sign} S_{NL}(t)) \tag{8}$$

$$S_{NL}(t)\dot{S}_{NL}(t) = -\eta S_{NL}(t)^2 - \eta\omega S_{NL}(t)\text{sign} S_{NL}(t)) \tag{9}$$

with $\eta > 0$, $\omega > 0$.

From (9) we are able to conclude that (7) holds $\forall t$. Moreover, it is obvious that to achieve the existence condition (7), condition (8) is mandatory. An adequate choice of the control law in (6) is the key solution to achieve (7). This is the subject of the next subsection.

3.2. **The control law.** The derivative of the sliding surface given by (6) is:

$$\dot{S}_{NL} = \frac{-K_1(1-u_{NL})}{L}\dot{x}_2 + \frac{K_1 x_2}{L}\dot{u}_{NL} + 2K_2 x_1 \dot{x}_1 \tag{10}$$

which, by taking into account (8), can be rewritten as:

$$\dot{S}_{NL} = -\eta(S_{NL}(t) + \omega \text{sign} S_{NL}(t)). \tag{11}$$

From (10) and (11) we get the derivative of the control law as follows:

$$\dot{u}_{NL} = \frac{L}{x_2 K_1}\left(\frac{K_1(1-u_{NL})}{L}\dot{x}_2 - 2K_2 x_1 \dot{x}_1 - \eta(S_{NL}(t) + \omega \text{sign} S_{NL}(t))\right). \tag{12}$$

It can be rewritten by replacing $\dot{x}_1$ and $\dot{x}_2$ by their expressions given in (2):

$$\begin{aligned}\dot{u}_{NL} = {} & \frac{(1-u_{NL})^2}{C}\frac{x_1}{x_2} - \frac{(1-u_{NL})}{RC} + \frac{2K_2 x_1}{K_1}(1-u_{NL}) - \frac{2K_2 x_1}{K_1}\frac{E}{x_2} \\ & - \frac{L}{K_1 x_2}\eta(S_{NL}(t) + \omega \text{sign} S_{NL}(t)).\end{aligned} \tag{13}$$

The control law given by (13) allows the sliding surface to comply with (11). It also infers to the sliding surface a decaying behavior or, in other words, an asymptotic stability feature. As a consequence, the sliding surface will go to zero when the time goes to infinity.

3.3. **Stability condition.** The stability of the system is guaranteed if the dynamic of the system in the sliding regime is directed toward the desired equilibrium point. In the preceding subsection, we proved that with the chosen control law (13), the sliding surface will reach the steady state $S_{NL}(t) = 0$ for t greater than a time t_r which corresponds to the settling time of the system described by (11). Our aim is to determine the dynamic of the variable state errors e_1 and e_2 when the sliding regime is reached, with $e_1 = x_1 - X_{1r}$ and $e_2 = x_2 - X_{2r}$.

Let $V_{NL} = \frac{1}{2}e_1^2$ be a candidate Lyapunov function. Its first derivative is

$$\begin{aligned} \dot{V}_{NL} &= e_1\dot{e}_1 \\ &= e_1\dot{x}_1. \end{aligned} \tag{14}$$

In order to insure that $\dot{V}_{NL} < 0$, the product $e_1\dot{x}_1$ must be negative. The expression of $\dot{x}_1$ is deduced from (5) with the constraint $S_{NL}(t) = 0$ as follows:

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

It is worth noting that assuming $S_{NL}(t) = 0$ means that the sliding regime is reached and this is ensured by the choice of the control law (13).

The derivative of V_{NL} is then given by

$$\begin{aligned} \dot{V}_{NL} = e_1\dot{x}_1 &= (x_1 - X_{1r})\left(-\frac{K_2}{K_1}(x_1^2 - {X_{1r}}^2)\right) \\ &= -\frac{K_2}{K_1}(x_1 - X_{1r})^2(x_1 + X_{1r}). \end{aligned}$$

The stability of $x_1(t)$ is guaranteed if K_1 and K_2 are positive. Therefore, $x_1(t) \to X_{1r}$ and $\dot{x}_1(t) \to 0$. By replacing $\dot{x}_1(t)$ by its expression given by (2), we deduce that if $\dot{x}_1(t) \to 0$ then $x_2(t) \to (\frac{E}{1-U}) = X_{2r}$ which implies the stability of $x_2(t)$. The choice $K_1 > 0$ and $K_2 > 0$ implies that the state $x(t)$ goes to the equilibrium point when the time t goes to infinity. This choice is the stability condition for the closed loop system.

4. **Comparison with Other Non-SMC Controllers.** In this section we aim at presenting a comparison between the Backstepping Controller (BC), the Parallel Damped Passivity-Based Controller (PDPBC) and the proposed approach developed in Section 3 which is defined as the PSMC approach.

4.1. **Backstepping Controller.** The backstepping approach is a recursive design methodology. It involves a systematic construction of both feedback control law and associated Lyapunov function:

$$V(x) = \frac{1}{2}z_1^2 + \frac{1}{2}z_2^2 \tag{15}$$

with $z_1 = x_1 - X_{1r}$ and $z_2 = a_2x_2 - \frac{1}{1-u}(k_{1b}z_1 + a_2E)$.

In order to have a negative derivative of the Lyapunov function, the control law has to satisfy:

$$\begin{aligned} \dot{u} = &-(1-u)^2\left(k_{1b}(x_1 - X_{1r}) + a_2E\right)^{-1}\left((1-u)^2 - k_{1b}^2\right)(x_1 - X_{1r}) \\ &-(k_{2b} + k_{1b})(1-u)\Bigg(a_2x_2 - \frac{1}{(1-u)}(k_{1b}(x_1 - X_{1r}) \\ &+a_2E) + a_2d(1-u)x_2 - a_2a_1x_1(1-u)^2\Bigg) \end{aligned} \tag{16}$$

where $a_1 = \frac{1}{C}$, $a_2 = \frac{1}{L}$ and $d = \frac{1}{RC}$.

4.2. **Parallel-Damped Passivity-Based Controller (PD-PBC).** The nonlinear passivity-based control (PBC) aims at modifying the energy of the system and injecting damping in order to modify the dissipation structure of the system. This damping injection can be made in series when the damping is added to the input current or in parallel when the damping is added to the capacitor voltages [6]. A simplified Parallel-Damped Passivity-Based Controller (PD-PBC) has been proposed in [5].

Following the expression for U in (4), the controller will assume the form:

$$u = 1 - \frac{E}{x_{2d}} \tag{17}$$

$$\dot{x}_{2d} = -f(x_{2d}, e_d) \tag{18}$$

where $x_{2d}(t)$ stands for the desired trajectory for $x_2(t)$. Moreover when $\dot{x}_{2d} = 0$, it is required that $e_{d\infty} = 0$ and $x_{2d\infty} = X_{2r}$.

The function $f(x_{2d}, e_d)$ is given by:

$$f(x_{2d}, e_d) = \frac{K_{1p} + K_{2p}}{C} x_{2d} + \frac{K_{2p}}{C} x_{2d} + \frac{K_{1p}}{C} X_{2r} \tag{19}$$

with $K_{1p} + K_{2p} > 0$.

As a consequence we get

$$\dot{x}_{2d} = -\frac{K_{1p} + K_{2p}}{C} x_{2d} + \frac{K_{2p}}{C} x_{2d} + \frac{K_{1p}}{C} X_{2r}. \tag{20}$$

4.3. **Simulation results.** In order to test the effectiveness and the robustness of the proposed sliding mode controller compared to other controllers, the average model of the DC-DC converter has been simulated using the Matab/Simulink software.

The simulations were performed with the following parameter's values:

$$R = 30\Omega, \quad L = 10\text{mH}, \quad C = 100\mu\text{F}, \quad E = 15\text{V}, \quad T_e = 50\mu\text{s}, \quad X_{2r} = 30\text{V}.$$

The initial values are:

$$x_1(0) = 0.6\text{A}, \quad x_2(0) = 16\text{V}, \quad u(0) = 0.1.$$

4.3.1. *Simulation results without variation.* Table 1 contains the design parameters values for the three considered methods: PSMC, BC and PDPBC.

TABLE 1. Design parameters for PSMC, BC and PDPBC

PSMC	BC	PDPBC
$K_1 = 0.0048$	$K_{1b} = 1100$	$K_{1p} = 0.3692$
$K_2 = 0.4$	$K_{2b} = 11000$	$K_{2p} = 0.4733$

TABLE 2. Comparison of results obtained from PDPBC, BC and PSMC

	PDPBC	BC	PSMC
Rise time (ms)	77.5149	257.4079	147.6051
Settling time (ms)	284.4814	448.1615	257.0769
Settling min (A)	1.8649	1.8599	1.8601
Settling max (A)	2.0668	1.9986	2
Overshoot (A)	3.3418	0	0
Peak (A)	2.0668	1.9986	2

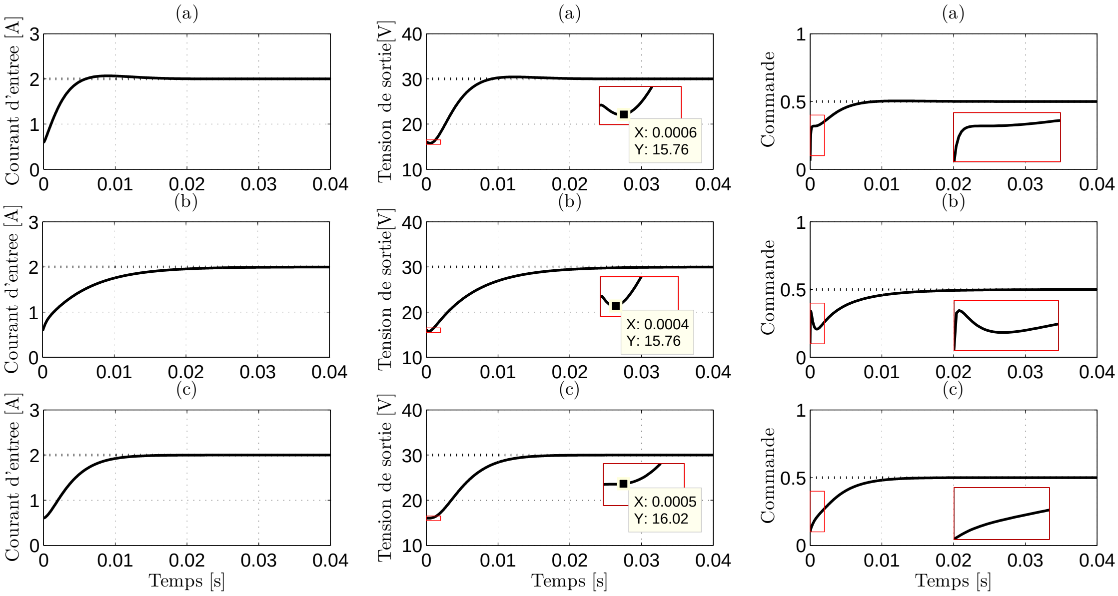

FIGURE 2. Simulation results of (a) PDPBC, (b) BC and (c) PSMC

TABLE 3. Parameters of PSMC, BC and PDPBC under load resistor variation

PSMC	BC	PDPBC
$K_1 = 0.0065$	$K_{1b} = 1200$	$K_{1p} = 0.3692$
$K_2 = 0.4$	$K_{2b} = 12000$	$K_{2p} = 0.4733$

4.3.2. *Simulation results under load resistor variation.* In order to compare the robustness of the PSMC with the PDPBC and BC, a load resistor change is applied from $R = 30\Omega$ (the nominal value) to $R = 45\Omega$ at $t = 0.05$s. Table 3 contains the parameters values of PSMC, BC and PDPBC under load resistor variation.

4.3.3. *Results discussion.* From Table 2, it is noticeable that the rise time reaches its minimum for the PDPBC approach and its maximum in the case of the BC. The PSMC approach achieves the minimum settling time. In addition, the PSMC shows the best tracking of the input current because the current reaches its desired value (2A) without overshoot. As a consequence, it can be concluded that the proposed controller, that is the PSMC approach, fulfills better performance than the other approaches.

It is clear from Figure 2 that the output voltage obtained for the three methods, the PDPBC, the BC and the PSMC performs good tracking of the reference (30V). However, the zoomed parts in Figure 2 show clearly that the non-minimum phase behavior is eliminated especially in the case of the PSMC.

Figure 3 shows that the BC behavior under load variation is better than the PDPBC in accordance with [22]. We can say that all tested controllers are robust and the output voltage tracking is achieved in all cases. However, it is noticeable from the duty ratio curves that the PSMC has the best behavior under load variation (the small peak visible in the case of the BC could be an undesirable behavior).

5. **Comparison with Other SMC Approaches.** In this section we compare our proposed SMC approach to the classic sliding mode approach (CSMC) [9], the approach based on a generalized PI Sliding Mode Control (GPISMC) proposed in [2, 3] and the

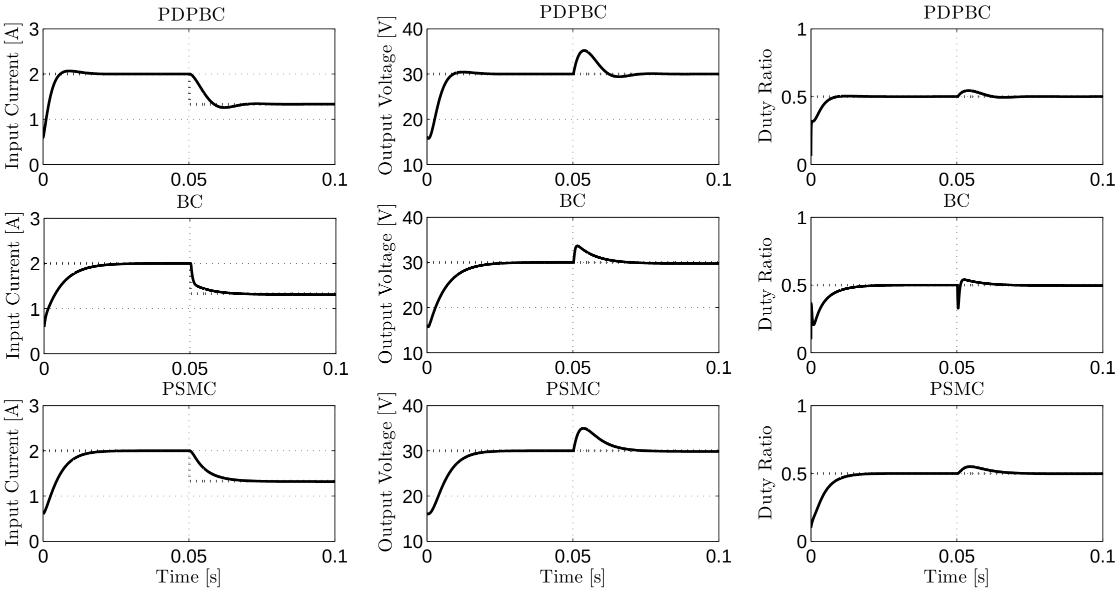

FIGURE 3. Simulation results of the PDPBC, the BC and the PSMC under load resistor variation

Sliding Mode Controller Based on an Extended Linearization (SMCBEL) as proposed in [10].

5.1. **Classic sliding mode controller.** In [9], a cascade control structure is applied to control the boost converter, which leads to solving the control problem using two control loops: the output voltage loop generates the reference current from the voltage error and the inner current loop controls the inductor current via a classic sliding mode controller:

$$u = \begin{cases} 1 & \text{for } S < 0, \\ 0 & \text{for } S > 0. \end{cases}$$

The sliding surface is:

$$S = K'_{1h}(x_2 - X_{2r}) + K_{2h}(x_1 - X_1 r) \tag{21}$$

with

$$K'_{1h} = K_{1h} - \frac{K_{2h}X_{2r}}{RE}. \tag{22}$$

The existence and stability conditions are verified if

$$\frac{K'_{1h}}{K_{2h}} < \frac{RCE}{X_{2r}L}$$

where K_{1h} and K_{2h} are positive scalars.

5.2. **Generalized PI sliding mode control.** The feedback control of the GPISMC described in [2, 3] uses only the output capacitor voltage measurement, as well as the available input signal, represented by the switch positions:

$$u_g(\tau) = \begin{cases} 1 & \text{for } S(\varepsilon_2, u_g) > 0, \\ 0 & \text{for } S(\varepsilon_2, u_g) < 0. \end{cases}$$

The GPISMC sliding surface is:

$$S(\varepsilon_2, u_g, \varepsilon_3) = \int_0^{\rho} (1 - u_g(\rho)\varepsilon_2(\rho))d\rho - \frac{{V_d}^2}{Q} + k_0\varepsilon_3 \tag{23}$$

with

$$\dot{\varepsilon_3} = z_2 - V_d, \quad \varepsilon_3(0) = 0 \tag{24}$$

where $\varepsilon_2 = \frac{x_2}{E}$, $\tau = \frac{t}{\sqrt{LC}}$, $Q = R\sqrt{\frac{C}{L}}$, $u_g = 1 - u$, $z_1 = \frac{x_1}{E}\sqrt{\frac{L}{C}}$, $z_2 = \frac{x_2}{E}$, $0 < k_0 < \frac{1}{V_d}$ and $V_d = \frac{X_{2r}}{E}$.

5.3. **Sliding mode controller based on extended linearization.** The design technique is based on an approximate linearization of the average model about parametrized equilibrium points [10]. The obtained linear system is then used with a classic sliding surface where the design parameters are chosen in order to guarantee the asymptotic stability of the autonomous ideal sliding mode dynamical system. The parametrized nonlinear sliding manifold is then constructed yielding the construction of the equivalent control and the definition of the sliding mode switching logic.

The proposed non linear sliding surface is:

$$S = b(z_1 - Z_1) + \frac{1}{2}c_1(z_1^2 - Z_1^2) + \frac{c_1 - 2w_1}{2}(z_2^2 - Z_2^2). \tag{25}$$

The equivalent control is given by:

$$U_{eq} = 1 - \frac{b(b + c_1 z_1) - w_1(c_1 - 2w_1)z_2^2}{w_0(b + c_1 x_1) - w_0(c_1 - 2w_1)z_1 z_2}. \tag{26}$$

Then, the sliding mode controller is:

$$u = \frac{1}{2}(1 + \mathrm{sign}S) \tag{27}$$

with

$$z_1 = x_1\sqrt{L}, \quad Z_1 = X_{1r}\sqrt{L}, \quad z_2 = x_2\sqrt{C}, \quad Z_2 = X_{2r}\sqrt{C},$$
$$w_0 = \frac{1}{\sqrt{LC}}, \quad w_1 = \frac{1}{RC}, \quad b = \frac{E}{\sqrt{L}}$$

and $c_1 > 0$ is the controller parameter.

5.4. **Simulation results.** In order to test the effectiveness and robustness of the proposed sliding mode controller, the average model of the DC-DC converter is used. The simulations are carried out using the Matlab/Simulink software. The simulations were performed with the same parameter values used in Section 4.3. A comparison of the PSMC (the proposed method) with the GPISMC, the CSMC and the SMCBEL is given.

5.4.1. *Simulation results.* Table 4 contains the design parameters values for the four approaches, that is, the PSMC, the GPISMC, the CSMC and the SMCBEL.

TABLE 4. Parameters of PSMC, GPISMC, CSMC and SMCBEL

PSMC	GPISMC	CSMC	SMCBEL
$K_1 = 0.0048$	$K_0 = 0.1$	$K_{1h} = 0.025$	$c_1 = 300$
$K_2 = 0.4$		$K_{2h} = 0.5$	

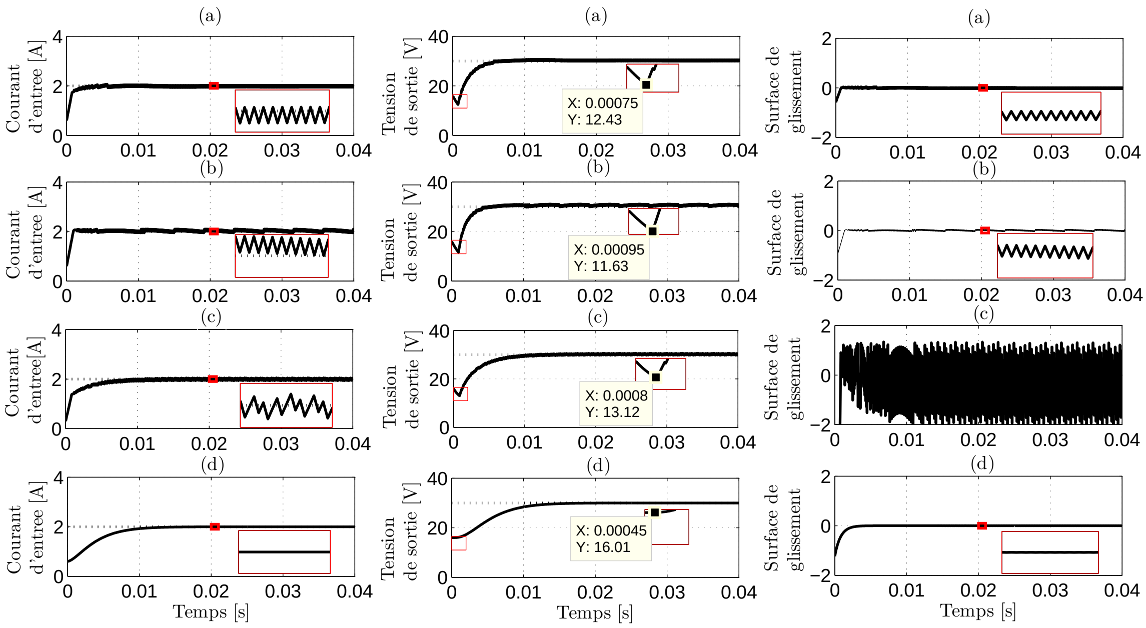

FIGURE 4. Simulation results of (a) CSMC, (b) GPISMC, (c) SMCBEL and (d) PSMC

TABLE 5. Comparison of results obtained from CSMC, GPISMC, SMCBEL and PSMC

	CSMC	GPISMC	SMCBEL	PSMC
Rise time (ms)	29.0261	15.1449	74.2235	147.6051
Settling time (ms)	800.6222	800.6194	800.5517	257.0769
Settling min (A)	1.8312	1.9442	1.7509	1.8601
Settling max (A)	2.0667	2.0958	2.0512	2
Overshoot (A)	2.4681	3.3418	0	0
Peak (A)	2.0667	2.0958	2.0512	2

TABLE 6. Parameters of PSMC, GPISMC, CSMC and SMCBEL under load resistor variation

PSMC	GPISMC	CSMC	SMCBEL
$K_1 = 0.00048$	$K_0 = 7$	$K_{1h} = 0.07$	$c_1 = 3000$
$K_2 = 0.03$		$K_{2h} = 0.5$	

5.4.2. *Simulation results under load resistor variation.* In order to test the robustness of the PSMC in comparison with the CSMC, the GPISMC and the SMCBEL, a load resistor change is applied from $R = 30\Omega$ (the nominal value) to $R = 45\Omega$ at $t = 0.3$s. Table 6 contains the parameters values of the PSMC, the GPISMC, the CSMC and the SMCBEL.

5.4.3. *Results discussion.* Table 5 shows clearly that the rise time is minimum for GPISMC and maximum in the case of the PSMC. However, the settling time is at its minimum value for the PSMC which can be interpreted as a good behavior. Indeed, a small rise time will need a large control but it does not imply a small settling time. If instead we have a bigger rise time giving rise to a moderate control but at the same time enough control allowing the system to settle rapidly. In addition, it can be noticeable, that the input current tracking with the PSMC is better because it reaches its desired value without

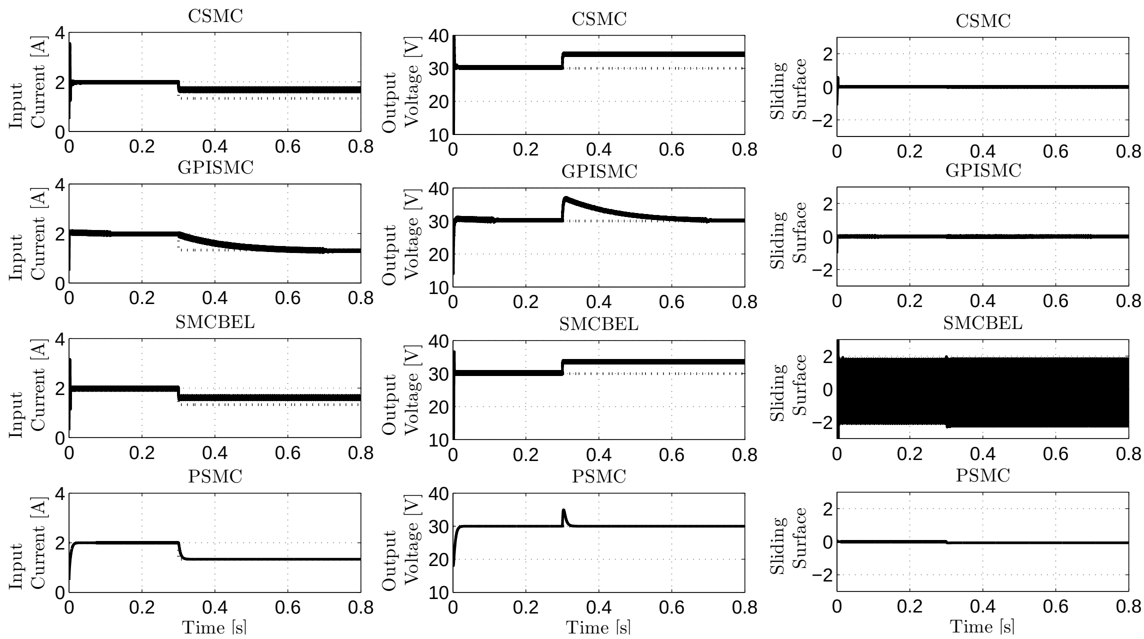

FIGURE 5. Simulation results of the CSMC, the GPISMC, the SMCBEL and the PSMC under load resistor variation

overshoot. Thus, it can be concluded that the proposed controller is the one that behaves well with respect to all aspects.

The zoomed parts in Figure 4 of the input current and the sliding surface show that the chattering phenomenon is totally eliminated in the case of the PSMC while the other approaches fail to do the same. Moreover, the PSMC is able to overcome the problem of the non-minimum phase compared to the GPISMC, the CSMC and the SMCBEL. Thus, a good output voltage tracking is obtained with the PSMC.

It can be seen from Figure 5, that the GPISMC and the PSMC are able to deal with the load variation. However, the CSMC and the SMCBEL exhibit a steady state error in the output voltage. The figure shows clearly that the PSMC behavior against a load variation is better than that of the GPISMC. This can be explained by the fact that the sliding surface used in the GPISMC contains an integral term which, in general, participates to slow down the system.

As a conclusion, the PSMC is able to deal efficiently with the problem of the output voltage steady state error as presented in [26] without requiring an adaptation of control parameters.

6. **Conclusions.** In this paper, a proposed sliding mode controller (PSMC) is compared to some existing controllers from the literature. The comparison is made first with two controllers which are not based on a sliding mode strategy, that is, the parallel damped passivity-based controller (PDPBC) [5] and the Backstepping Controller (BC) [4, 8, 15]. The second comparison is made with some controllers which are based on a sliding mode control strategy, that is, the classic sliding mode controller (CSMC) from [9], the generalized PI sliding mode controller (GPISMC) from [2, 3] and the sliding mode controller based on extended linearization (SMCBEL) from [10].

Through comparative computer simulations, the PSMC has been shown to have an improved performance and a robust stability and it is able to eliminate the chattering phenomenon and the non-minimum phase problem.

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