

A new Backstepping Sliding Mode Controller applied to a DC-DC Boost Converter

Yosra Massaoudi*, Dorsaf Elleuch*, Jean Paul Gaubert**, Driss Mehdi**, and Tarak Damak*

*University of Sfax, National School of Engineering of Sfax, Lab-STA, PB 1173, 3038 Sfax, Tunisia

**University of Poitiers, LIAS-ENSIP, Bat.B25-2, Rue Pierre Brousse- BP633, 86 022 Poitiers Cedex, France

Article Info

Article history:

Received Feb 07, 2016

Revised Jul 26, 2016

Accepted Aug 8, 2016

Keyword:

Boost converter
non minimum phase
chattering phenomenon
super twisting SMC
backstepping SMC.

Corresponding Author:

Yosra Massaoudi,
University of Sfax, National School
of Engineering of Sfax, Lab-STA,
PB 1173, 3038 Sfax, Tunisia,
yosra.massaoudi1@gmail.com

ABSTRACT

In order to deal with the boost converter non minimum phase property and to solve the Sliding Mode Control (SMC) major problem (the chattering phenomenon), a new backstepping Sliding Mode Controller is developed. In this paper, a comparative study between the proposed controller and the (2-SMC)super twisting and the classical SMC is provided in order to evaluate each controller. Simulations and experimental results show the effectiveness and the robustness of the proposed controller with respect to load variation.

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1. INTRODUCTION

The boost converter is widely used in renewable energy area and in particular solar energy ([1, 2, 12, 15]) since it allows to maintain a desired output voltage despite the fluctuation of the input voltage produced by the renewable energy source. However, the output voltage, which is the variable to be regulated, is a non minimum phase output (due to the boost converter inherent Right Half Plane-zero).

Many approaches and techniques, such as, the Parallel Damped Passivity Based Controller [17], the Backstepping Controller (BC) [5] and the Sliding Mode Controller (SMC) [10], have been proposed to deal with the non-minimum phase behavior. They provide a fast transient response and cope with the boost converter parameter variations.

Previous work by the authors, [10], show that the Backstepping Controller and the Parallel Damped Passivity Based Controller have a good tracking and robustness performance but in the same time fail to solve the boost non minimum phase problem. Moreover, despite the well admitted effectiveness and robustness of SMC strategies, [18], the chattering phenomenon remains the major drawback of the approach, [18].

Many solutions have been proposed to overcome the chattering problem and to mitigate the non minimum phase boost problem. For instance [7] proposes a new sliding surface giving rise to an integral SMC or a double integral SMC. The obtained controller reduces the chattering phenomenon but fails to suppress it.

The second order SMC (2-SMC) has been proved to be a good solution for the chattering problem. Indeed, for different variant of the 2-SMC, that is, with the twisting algorithm, with the terminal algorithm or with the quasi continuous algorithm, the chattering is eliminated.

Nowadays, the (2-SMC) with super-twisting algorithm is preferable since it reduces the chattering phenomenon in many applications. Moreover, in the case of a boost converter, it is able to mitigate the non minimum phase behavior [4]. In addition, combining the SMC with others approaches gave rise to many new approaches such as a PI controller in [16], a fuzzy controller in [19] and a backstepping controller in [14].

Through the backstepping Sliding Mode Controller (BSMC), one can take the advantages of both methods by improving the Backstepping robustness and eliminating the Sliding Mode Controller chattering phenomenon [6].

In this paper, a comparative study between the super twisting (2-SMC) and the backstepping SMC with the classical SMC is provided in order to show the advantages of each controller especially in terms of chattering phenomenon reduction and non minimum phase behavior mitigation.

The paper is organized as follows: Section 2 presents the modeling of the boost converter. In section 3, the proposed backstepping Sliding Mode Controller is presented. Section 4 is devoted to recall the classical SMC and the (2-SMC) with super twisting controller. The effectiveness and the robustness of the proposed approaches are verified through simulation in section 5 and experimentally verified in section 6. Some conclusions end the paper in section 7.

2. BOOST CONVERTER MODELLING

The ideal boost converter given by Figure 1 contains a MOSFET (an active switch), a diode, an inductor L , a capacitor C , a load resistance R . We notice that E is the input voltage, V_s is the output voltage and u is the duty cycle:

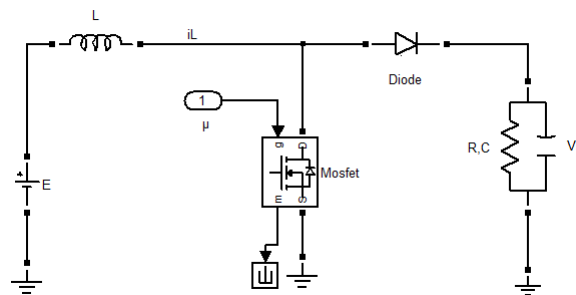


Figure 1. Boost converter

The average Boost converter model is given by the following equations:

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

where: x_1 is the input current average value, x_2 is the output voltage average value and u is the duty ratio.

Let X_{1r} be the input current reference value (constant), then the equilibrium values of $x_{1\infty} = X_{1r}$, $x_{2\infty} = X_{2r}$ and $u_{\infty} = U$ ($0 < U < 1$) satisfy the following equations:

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

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

The relation between X_{1r} and X_{2r} is given by:

$$X_{1r} = \frac{X_{2r}^2}{RE} \quad (4)$$

3. THE PROPOSED BACKSTEPPING SLIDING MODE CONTROLLER

The backstepping sliding mode controller is composed of the backstepping control law u_{BC} and a discontinuous sliding mode control law u_{dis} .

3.1. The backstepping control law

The backstepping design control is a recursive Methodology. It Involves a systematic building of both feed-back control law and the associate Lyapunov function ([5, 9]).

The backstepping controller will be designed in two steps since the boost converter is a second order system.

The first step:

The output error is defined by:

$$e_1 = x_1 - X_{1r} \quad (5)$$

The output error derivative is:

$$\dot{e}_1 = \dot{x}_1 = -\frac{(1-u)}{L}(1-u)x_2 + \frac{E}{L} \quad (6)$$

We will suppose that x_2 is defined as follows:

$$x_2 = \frac{L}{(1-u)}(c_1 e_1 + \frac{1}{L}E) \quad (7)$$

Thus: $\dot{e}_1 = -c_1 e_1$ and we deduce that $\frac{x_2}{L}$ behaves as a control variable of e_1 and its virtual expression is given by:

$$\alpha_1 = \frac{1}{(1-u)}(c_1 e_1 + \frac{1}{L}E) \quad (8)$$

The second step

Considering that $e_2 = \frac{x_2}{L} - \alpha_1$ the error between the real and the virtual controllers. The derivative of e_1 can be rewritten as follows:

$$\dot{e}_1 = -(1-u)(e_2 + \alpha_1) + \frac{E}{L} = -(1-u)e_2 - c_1 e_1 \quad (9)$$

In order to know the behavior of e_2 , we calculate its derivative:

$$\dot{e}_2 = \frac{\dot{x}_2}{L} - \dot{\alpha}_1 \quad (10)$$

$$\dot{\alpha}_1 = \frac{\dot{u}}{(1-u)^2}(c_1 e_1 + \frac{E}{L}) + \frac{c_1}{(1-u)}\dot{e}_1 = \frac{\dot{u}}{(1-u)^2}\alpha - \frac{c_1}{(1-u)}((1-u)e_2 + c_1 e_1) \quad (11)$$

Then, the derivative of e_2 is:

$$\dot{e}_2 = (1-u(t))\frac{x_1(t)}{LC} - \frac{x_2(t)}{RLC} + \frac{\dot{u}}{(1-u)^2}\alpha + \frac{c_1}{(1-u)}((1-u)e_2 + c_1 e_1) \quad (12)$$

We will consider the following Lyapunov function:

$$V = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 \quad (13)$$

The derivative of V is given by:

$$\dot{V} = e_1 \dot{e}_1 + e_2 \dot{e}_2 = -c_1 e_1^2 + e_2(\dot{e}_2 - (1-u)e_1) \quad (14)$$

Assuming that $-c_2 e_2 = \dot{e}_2 - (1-u)e_1$, we deduce that

$$\dot{V} = -c_1 e_1^2 - c_2 e_2^2. \quad (15)$$

The control law must satisfy the following condition:

$$\begin{aligned} (1-u)^2 e_1 - c_2(1-u)e_2 &= -\frac{1}{RLC}(1-u)x_2 + \frac{1}{LC}x_1(1-u)^2 \\ &- \frac{\dot{u}}{(1-u)}\alpha_1 + c_1((1-u)e_2 + c_1 e_1) \end{aligned} \quad (16)$$

which yields

$$\begin{aligned} \dot{u} &= (1-u)^2(c_1 e_1 + \frac{E}{L})^{-1}(((1-u)^2 - c_1^2)e_1 + (c_1 + c_2)(1-u)e_2 \\ &+ \frac{1}{RLC}(1-u)x_2 - \frac{1}{LC}x_1(1-u)^2). \end{aligned} \quad (17)$$

3.2. The discontinuous sliding mode control law

The sliding surface is given by:

$$S = K_1 e_1 + K_2 e_2. \quad (18)$$

The discontinuous sliding mode control law can be written as follows [13]:

$$u_{dis} = -k \frac{S}{|S| + \delta}. \quad (19)$$

3.3. The backstepping sliding mode control law

The proposed backstepping sliding mode control law is given by:

$$\begin{aligned} u &= u_{BC} + u_{dis} & (20) \\ \dot{u}_{BC} &= (1-u)^2 (c_1 e_1 + \frac{E}{L})^{-1} (((1-u)^2 - c_1^2) e_1 + (c_1 + c_2)(1-u) e_2 \\ &+ \frac{1}{RLC} (1-u) x_2 - \frac{1}{LC} x_1 (1-u)^2). & (21) \end{aligned}$$

4. RECALL OF THE CLASSICAL SMC AND THE SECOND ORDER SMC WITH SUPER TWISTING

4.1. The classical sliding mode controller

In [8], a classical sliding mode controller is given as follows:

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

The sliding surface is:

$$S = K_1 (x_1 - X_{1d}) + K_2 (x_2 - X_{2r}) \quad (22)$$

with: $X_{1d} = \frac{X_{2r} x_2}{RE}$: the input current reference value.

The sliding surface can be rewritten as follows:

$$S = K_1 (x_1 - X_{1r}) + K_2' (x_2 - X_{2r}) = K_1 e_1 + K_2' e_2 \quad (23)$$

with:

$$K_2' = K_2 - \frac{K_1 X_{2r}}{RE}. \quad (24)$$

The existence and stability conditions are verified if

$$\frac{K_2'}{K_1} < \frac{RCE}{X_{2r}L}$$

where K_1 and K_2 are positive scalars [8].

4.2. Second order sliding mode controller with super twisting

The super twisting control algorithm is given by [11]:

$$u = u_1 + u_2 \quad (25)$$

$$\dot{u}_1 = -\beta \text{sign}(S) \quad (26)$$

$$u_2 = -\alpha |S|^\rho \text{sign}(S) \quad (27)$$

with: $\alpha > 0$, $\beta > 0$ and $\rho = 0.5$

5. SIMULATION RESULTS

In order to test the effectiveness and the robustness of each controller, 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 and the initial values are:

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

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

CSMC parameters: $K_1 = 0.01, K_2 = 0.5$

(2-SMC)ST parameters: $K_1 = 0.01, K_2 = 5, \beta = 0.1, \alpha = 0.1$

BSMC parameters: $c_1 = 700, c_2 = 7000, K_1 = 50, K_2 = 1, k = 0.01, \delta = 0.5$.

5.1. Reference variation:

In this experiment, the current reference variation switches from 2A to 3A at 0.05s. The desired values of the output voltage and the duty ratio are given by Table 1.

Table 1. Desired values of the output voltage and the duty ratio

	CSMC	(2-SMC)ST	BSMC
$X_{1r}(A)$		2	3
$X_{2r}(V)$		30	36.74
U		0.5	0.6

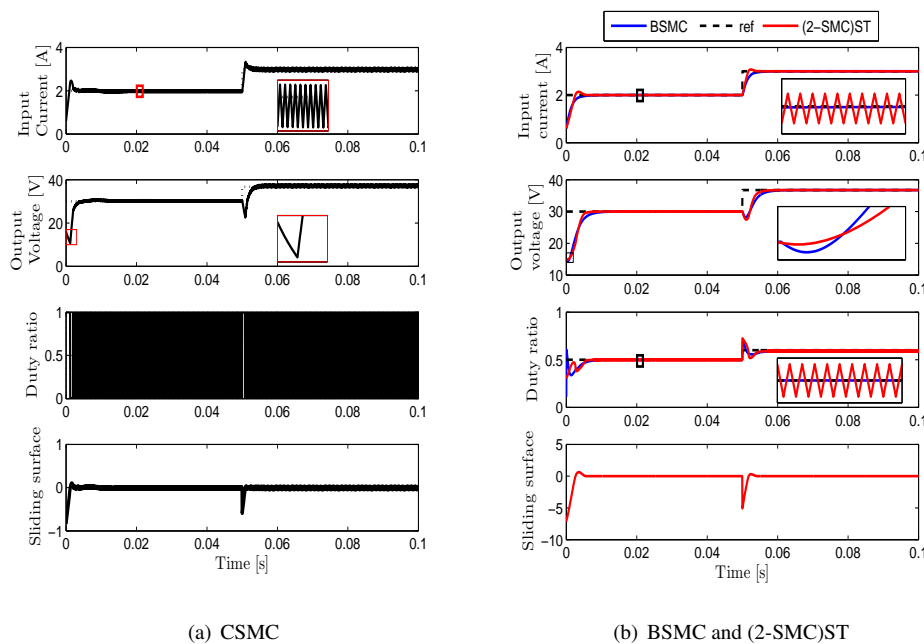


Figure 2. Simulation results with reference variation

Table 2. Performances of the CSMC, (2-SMC)ST and the BSMC.

Rise time $\pm 5\%$ (ms)	0.7157	3.2	2.9
Settling time (ms)	2.05	2.35	3.5
Overshoot (A)	26.5254	6.7929	0
Peak (A)	2.4571	2.0769	2

We notice from Figure 2, that the input current and the output voltage tracking are effective in all cases. However, we can say from Table 2 that the BSMC approach outperforms the other approaches since it reaches its desired value with no overshoot and no peak value and with a relative small settling time. The zoomed parts in Figure 2 show that the chattering phenomenon presented in the case of the CSMC is reduced by the (2-SMC)ST and totally eliminated by the BSMC and non-minimum phase behavior seen plainly in the CSMC output voltage is mitigated by the BSMC and well improved by the (2-SMC)ST.

5.2. Load resistor variation

In order to evaluate the robustness of the proposed controllers, a load resistor variation is applied from $R = 30\Omega$ to $R = 15\Omega$ at $t = 0.5s$ in the case of CSMC and BSMC and at $t = 2s$ in the case of (2-SMC)ST (in order to see clearly the response).

The desired values of the output voltage and the duty ratio are given by Table 3.

Table 3. Desired values of the output voltage and the duty ratio.

	CSMC	(2-SMC)ST	BSMC
$R(\Omega)$		30	15
$X_{1r}(A)$		2	2
$X_{2r}(V)$		30	21.21

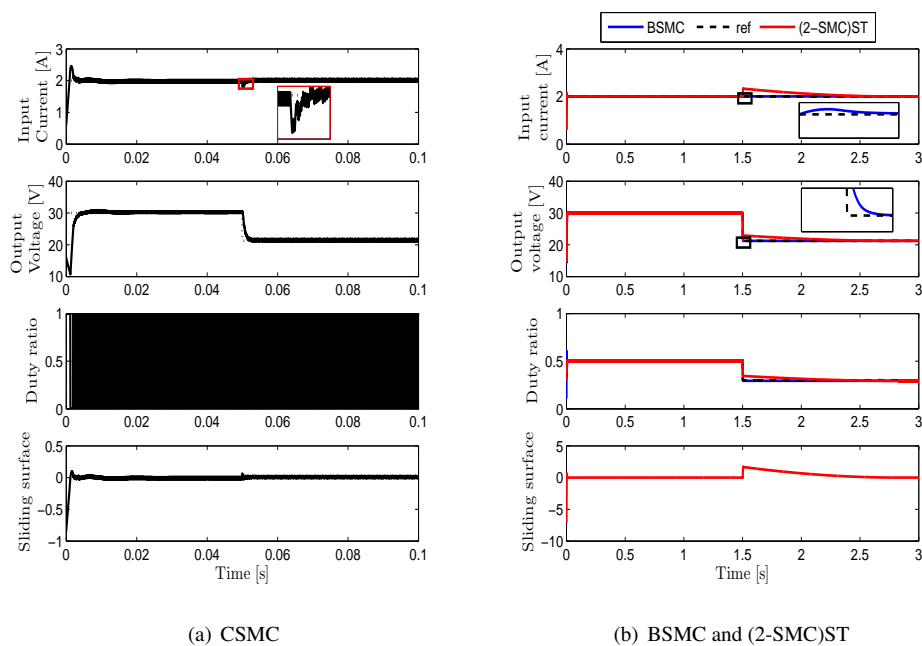


Figure 3. Simulation results with load resistor variation

It can be seen from Figure 3 that all controllers are robust. However, the BSMC behavior against a load variation is better than the CSMC (elimination of chattering) and faster than the (2-SMC)ST. This is explained by the fact that the (2-SMC)ST control law contains an integral term which slow down the system.

6. EXPERIMENTAL RESULTS

These controllers were experimentally evaluated on the real system available in the LIAS laboratory.

6.1. Experiments in open loop

Experiments in open loop presented by Figure 4 show a difference between the theoretical output voltage value and the experimental output voltage value. The same phenomenon is noticed for the input current. The neglected internal resistor of the inductor and the MOSFET in the on-state and the threshold voltage with the dynamic resistance of the diode could be a source of these errors [3].

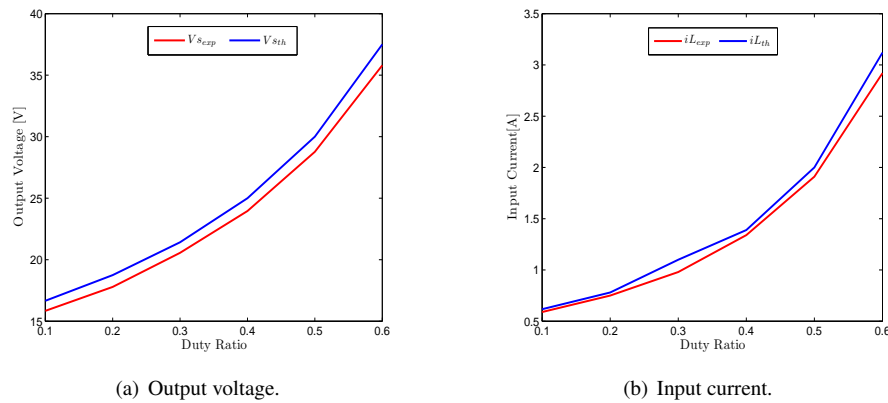


Figure 4. Experimental curves in open loop.

6.2. Experiments in closed loop

The controllers implementation was carried out using the DSP-based system DS1104 developed by DSpace. **Reference Variation:**

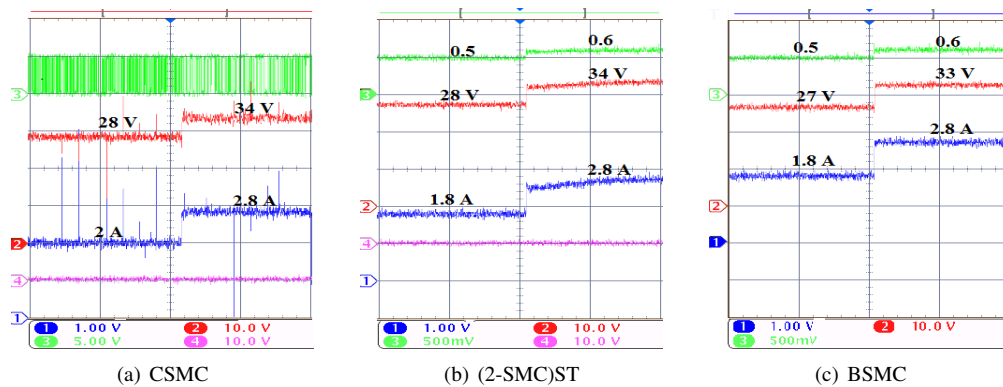


Figure 5. Experimental results with reference variation: 1- The input current $i_L(t)$; 2- The output voltage $V_s(t)$; 3- The duty cycle $u(t)$; 4- The sliding surface.

Figure 5 shows that the experimental results are similar to the simulation results and the state error is justified by neglecting the internal resistors of the inductance, the MOSFET and the diode as well as the diode threshold voltage and the switching transient behavior for semiconductors as shown in Figure 4.

The BSMC and the (2-SMC)ST are able to eliminate the chattering phenomenon which appears in the case of CSMC and which is undesirable for power converters. However, the BSMC is faster than the (2-SMC)ST. **Load resistor Variation:**

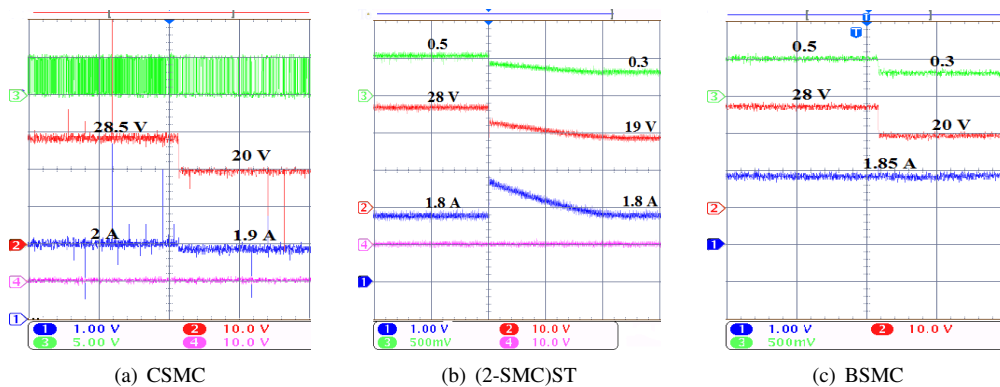


Figure 6. Experimental results with load resistor variation: 1- The input current $i_L(t)$; 2- The output voltage $V_s(t)$; 3- The duty cycle $u(t)$; 4- The sliding surface.

It is observable from Figure 6 that the BSMC is more robust than the CSMC and the (2-SMC)ST and it is insensitive to a load resistor variation. However, the (2-SMC)ST takes its time to reach the desired value under a load resistor variation. A similar behavior is reported in [20].

7. CONCLUSION

In this paper, we developed a new backstepping sliding mode controller (BSMC applied to a DC-DC Boost converter. In order to verify the effectiveness and the robustness of this controller, a comparative study with the classical Sliding Mode Controller and the Super twisting Sliding Mode Controller (2-SMC)ST was presented. We conclude that the chattering phenomenon which is the major problem of classical SMC is reduced by the (2-SMC)ST and totally eliminated by the BSMC. However, the non minimum phase behavior is mitigated by the BSMC and well improved by the (2-SMC)ST.

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BIOGRAPHY OF AUTHORS



Yosra Massaoudi received her diploma in Electrical Engineering from the National School of Engineers of Sfax, Tunisia, in 2010. From the same school, she received her M. S. degree in Automatic and Industrial Informatics and the Ph. D. in Electrical Engineering, in 2011 and 2015 respectively. She is currently a doctor in the Laboratory of Sciences and Techniques of Automatic and Computer Engineering Lab-STA, University of Sfax. Her research interests include boost converters modelling and control, nonlinear control and especially sliding mode control.



Dorsaf Elleuch received, from the Higher School of Sciences and Technique of Tunisia, her M. S degree in Electrical Engineering in 2005 and her M. S degree in Automatic-Product in 2007. She had the PHD degree in Automatic and Industrial Informatics in 2011 from the National School of Engineers of Sfax Tunisia. She is currently an assistant Professor in ISSAT Gafsa , Tunisia. Her current research interests are in the fields of robust sliding mode control and observers, Robots control, photovoltaque systems.



Jean Paul Gaubert was born in France in 1965. He received the Engineer's degree in electrical engineering from the University of Clermont-Ferrand, France, in 1988, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Science and Technology of Lille, Lille, France, in 1990 and 1992, respectively. He is currently an Associate Professor with the Automatic Control and Industrial Data Processing Laboratory (LAI), Poitiers National School of Engineering (ESIP), University of Poitiers, Poitiers, France. His current research interests are the modeling and advanced control of power converters and power electronics systems and their digital control techniques. The derived topics deal with power quality, such as active filters, pulse width modulation rectifiers, or renewable energy systems.



Driss Mehdi received an engineer degree from Mohammadia Engineering School, Rabat, Morocco in 1979 and a Ph. D. degree in automatic control from Nancy University in 1986. He was a senior lecturer from 1988 to 1992 at Louis Pasteur University in Strasbourg and since 1992 he has been professor at the University of Poitiers. His research interests include automatic control, robust control, delay and descriptor systems.



Tarak Damak received his diploma in Electrical Engineering from the National School of Engineers of Sfax, Tunisia, in 1989 and his D.E.A degree in Automatic Control from the Institut National des Sciences Appliquées de Toulouse, France, in 1990. He received his Ph.D. from the Université Paul Sabatier de Toulouse, France, in 1994. In 2006. He then obtained the University Habilitation from the National School of Engineers of Sfax. He is currently a professor in the Department of Mechanical Engineering of the National School of Engineers of Sfax, Tunisia. His current research interests are in the fields of distributed parameter systems, sliding mode control and observers, adaptive nonlinear control.