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# Comparative Analysis of Control Techniques Based Sliding Mode for Transient Stability Assessment for Synchronous Multicellular Converter

Rihab Hamdi, Amel Hadri Hamida, Fatiha Khelili, Sakina Zerouali, Ouafae Bennis

***Abstract*****—**This paper features a comparative study performance of sliding mode controller (SMC) for closed-loop voltage control of direct current to direct current (DC-DC) three-cells buck converter connected in parallel, operating in continuous conduction mode (CCM), based on pulse-width modulation (PWM) with SMC based on hysteresis modulation (HM) where an adaptive feedforward technique is adopted. On one hand, for the PWM-based SM, the approach is to incorporate a fixed-frequency PWM scheme which is effectively a variant of SM control. On the other hand, for the HM-based SM, oncoming an adaptive feedforward control that makes the hysteresis band variable in the hysteresis modulator of the SM controller in the aim to restrict the switching frequency variation in the case of any change of the line input voltage or output load variation are introduced. The results obtained under load change, input change and reference change clearly demonstrates a similar dynamic response of both proposed techniques, their effectiveness is fast and smooth tracking of the desired output voltage. The PWM-based SM technique has greatly improved the dynamic behavior with a bit advantageous compared to the HM-based SM technique, as well as provide stability in any operating conditions. Simulation studies in MATLAB/Simulink environment have been performed to verify the concept.

***Keywords*****—**Sliding mode control, pulse-width modulation, hysteresis modulation, DC-DC converter, parallel multi-cells converter, robustness.

## I. Introduction

In the field of strong currents with high switching frequencies, while automating technological processes, there is a tendency to develop and use new structures based on the combination of components. Among them, we find the parallel multicellular converters that have been receiving increased attention recently.

Various control methodologies are currently being considered to achieve a constant output voltage and have been found to have potential applications in DC-DC converters that require very high performance in dynamical response [1].

Theoretically, to achieve a sliding mode control operation in a perfect way, the system should be operated at a high switching frequency so that the controlled variables can follow closely the reference to achieve the desired dynamic response and steady-state operation. Along with this requirement, however, the feasibility of applying SM control to DC-DC converters is questioned [2]. This is because extreme high-speed switching in DC-DC converters leads to an excessive switching loss, inductor and transformer core losses, and "electromagnetic interference" noise issues. Hence, their switching frequencies must be constricted within clearly defined margins in order to make the SM control applicable to DC-DC converters. Therefore, the design of such converters is a challenge for electrical engineers due to the use requirements and the inherent nonlinear nature. All the converters have few requirements like high density which leads to a smaller size, high efficiency which leads to low losses, in the same line, they must be robust to any changes in the input or output [3], [4]. For surpassing the problem of high frequency, a new class of power converter appeared: the multicellular converter. The multicellular conversion has inherent advantages that make it an increasingly attractive solution that can be considered for any application. It provides more degrees of freedom to the designer, but it also makes the design more complicated since many options can be considered [5]. Thus, to generate a control signal, an equivalent control derived by applying the SM control technique is introduced to be compared with the fixed-frequency ramp in the modulator. The implementation of such a controller requires a relationship between SM control and duty-ratio control [6], [7]. The PWM strategy can be applied to develop fixed-frequency SM controllers and the technique of state-space averaging was incorporated into the controller's modeling [8]-[12]. Hereon, PWM duty-ratio control can be directly applied to the implementation of SM controllers. In turn, as known, the limitation of the conventional HM based sliding mode controller consists of the significant variation of the switching frequency in the presence of disturbances and parametric uncertainties. This disadvantage leads to overestimating the properties of the filters in the converter and to impropriate modifications of the regulation. Hence, it is recommended to operate the converter at a constant switching frequency [13]. To surpass this problem, we propose an adaptive controller with a feedforward technique in intent to overcome the imperfect feedback loop that causes a small steady-state error in the output voltage [14]-[17]. Unlike the feedback technique, that needs a perception of a past situation, the feedforward technique is illustrated in the formulation of commands to propose solutions for the future. In other words, it consists of the anticipation of the action that follows.

The major contribution of this work is to present thorough a discussion of the steady-state response, stability assessment and robustness analysis of the two strategies of control and to

Rihab Hamdi is with the University of Biskra, Algeria (e-mail: rihab.hamdi2012@gmail.com).

carry-out witch one is more effective and more suitable for the system.

The remainder of the paper is organized into 5 sections: Section II outlines the system's topology and operating principles. Section III discusses the control scheme and the operating mechanism of the PWM-based SMC and the HM-based SMC. Simulation results are presented and discussed in Section IV; Section V concludes the paper.

## II. Parallel Multi-Cell Converters

DC-DC converters constitute a particular class of nonlinear, time-varying systems. The multicellular converter is based on the combination of elementary cells of commutation. The signal is equal to 1 when the cell upper switch is conducting and equal to 0 when the lower complementary switch is conducting. These cells are associated in parallel with an RL load and separated by capacitors application to a three-cell buck converter. Fig. 1 depicts a basic topology of the buck converter, in which $V_i$ is the input DC voltage; L is the filter inductor; C is the capacitor; R is the load. Then the system dynamics of the buck converter can be expressed as:

$$L\frac{di_L}{dt} = -i_L - V_{out} + u.V_i \quad (1)$$

$$C\frac{dV_{out}}{dt} = i_L + \frac{V_{out}}{R} \quad (2)$$

where $i_L$ is the inductor current, $V_{out}$ is the output DC voltage, $u$ is the control input.

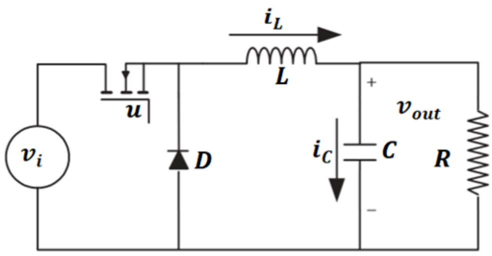


Fig. 1 Basic topology of the Buck converter

The multicellular converter consists of phases, where each cell contains two complementary power electronics components and it is controlled by a binary switch. A 3-phase converter feeds a single load assumed to be resistive. The considered multicellular buck converter is a second-order converter, with Single Input Single Output (SISO) structure, where, the cells are associated in parallel with R load, realized in MATLAB/Simulink.

Fig. 2 illustrates the configuration adopted of the three-cell step-down DC-DC converter associated with parallel realized in the MATLAB/Simulink environment.

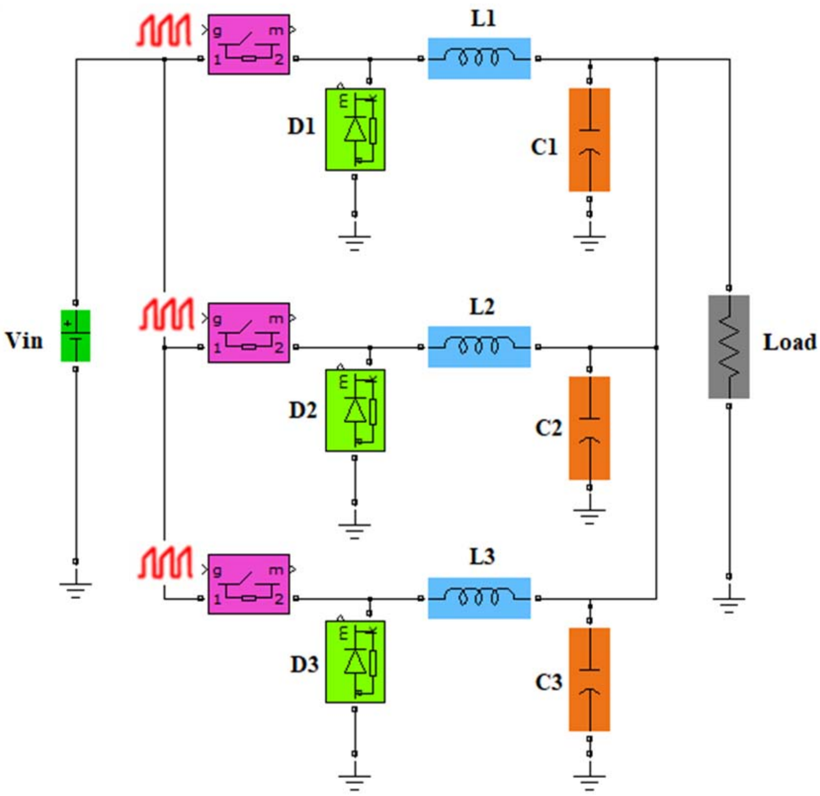


Fig. 2 Three-cell Buck converter associated in parallel

Table I shows the specifications of the buck converter used in the MATLAB simulation.

TABLE I
SPECIFICATIONS OF BUCK CONVERTER

| Description | Parameter | Nominal Value |
|---|---|---|
| Input voltage | Vi | 24 V |
| *Capacitance* | C | 6e-6 F |
| *Inductance* | L | 0.1 H |
| *Resistance* | R | 12 Ω |
| *Switching frequency* | *fw* | 20 kHz |
| *Desired out-put voltage* | Vref | 12 V |

## III. THE OPERATING MECHANISM

### A. PWM-Based SM Control

The proposed controller-based SM control via fixed-frequency PWM is applied to buck type DC/DC converter as shown in Fig. 3. Careful examination of controller equations reveal that it basically adopts the same structure as the PWM proportional derivative (PD) linear control, but with additional components consisting of the input voltage and the output voltage. These components are contributing to the nonlinearity of the feedback control, and therefore they are the key properties keeping the controller robust.

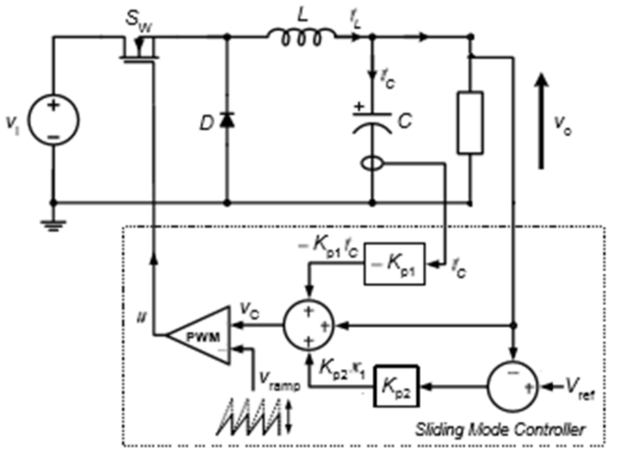


Fig. 3 PWM-based SM control scheme

For the system modeling and state-space descriptions required for the design of SM voltage control for buck converter operating in CCM, the state-space may be expressed in the following form:

$$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & \frac{-1}{RC} & 0\\ 1 & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix}+\begin{bmatrix}0\\ \frac{V_i}{LC}\\ 0\end{bmatrix}u+\begin{bmatrix}0\\ \frac{V_{out}}{LC}\\ 0\end{bmatrix} \tag{3}$$

To ensure the existence of SM operation, the local reachability condition presented by the following equation must be taken into consideration:

$$\lim_{S\to 0} S.\dot{S} < 0 \tag{4}$$

which gives:

$$0 < -L\left(\frac{\alpha_1}{\alpha_2}-\frac{1}{RC}\right)i_C + LC\frac{\alpha_3}{\alpha_2}\left(V_{ref}-V_{out}\right)+V_{out} < V_i \tag{5}$$

The selection of sliding coefficients for the controller of each converter must comply with its stated inequalities. Then, as where $u_{eq}$ is continuous and $0 < u_{eq} < 1$, the control equation for the PWM-based SM controller is derived as:

$$0 < -\frac{L}{V_i}\left(\frac{\alpha_1}{\alpha_2}-\frac{1}{RC}\right)i_C + \frac{LC}{V_i}\frac{\alpha_3}{\alpha_2}\left(V_{ref}-V_{out}\right)+\frac{V_{out}}{V_i} < 1 \tag{6}$$

### B. HM-Based SM Control

Hereby, the control scheme and the operating mechanism of the hysteresis band are represented which allows to evaluate the performance of the proposed controller under a wide range of operating points.

The proposed controller-based SM control via HM is applied to buck type DC-DC converter as shown in Fig. 4.

The mathematical model is developed:

$$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\end{bmatrix}=\begin{bmatrix}0 & 1\\ \frac{-1}{LC} & \frac{-1}{RC}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}0\\ -\frac{V_i}{LC}\end{bmatrix}u+\begin{bmatrix}0\\ \frac{V_{ref}}{LC}\end{bmatrix} \tag{7}$$

The sliding surface is defined as:

$$S=\frac{1}{R}\left(V_{ref}-V_{out}\right)-i_C \tag{8}$$

Also, the width of the hysteresis band κ is a fixed parameter that can be determined using:

$$\kappa=\frac{V_{ref}\left(1-\frac{V_{ref}}{V_i}\right)}{2fwL} \tag{9}$$

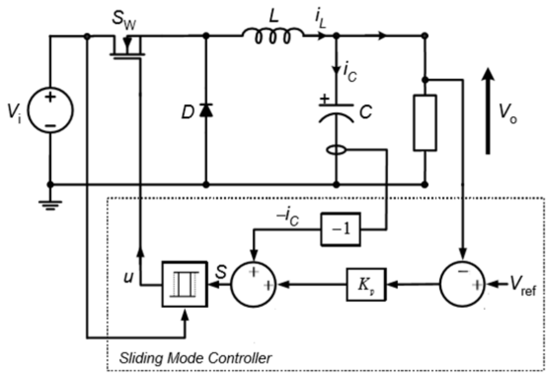


Fig. 4 HM-based SM control scheme

## IV. SIMULATION RESULTS

In order to illustrate the performance of the proposed control, we considered a three-cell converter connected to an R load. The performances of the developed techniques based SM control were verified through simulation using MATLAB software.

To test the performance of both proposed controllers, a comprehensive simulation under step load change (variation of 50%) with constant input voltage was tested. The reference output voltage was set to 12 V, the load resistance changes from 12 Ω to 6 Ω. The situation where the load changes suddenly from one value of load resistance to another is considered. This is particularly interesting because it is a typical problem for power electronics, where the power supply is supposed to compensate quickly for the load variation.

Robustness test versus the load resistance variation is illustrated by Fig. 5, showing that the state variables exhibit a transient but the output voltage converges to the desired reference. Then, the multicellular converter is initially powered by an input voltage $V_i = 24\,V$ which varies at instant $t = 0.4\,s$ to reach 50 V, to test the robustness of the developed two controllers, the disturbance is assigned to the level of the supply voltage. Fig. 6 summarizes the results of this test. There is a very brief transient that lasts a few $ms$ followed by a steady-state giving voltage values $V_{out}$ proportional to the new value of $V_i$.

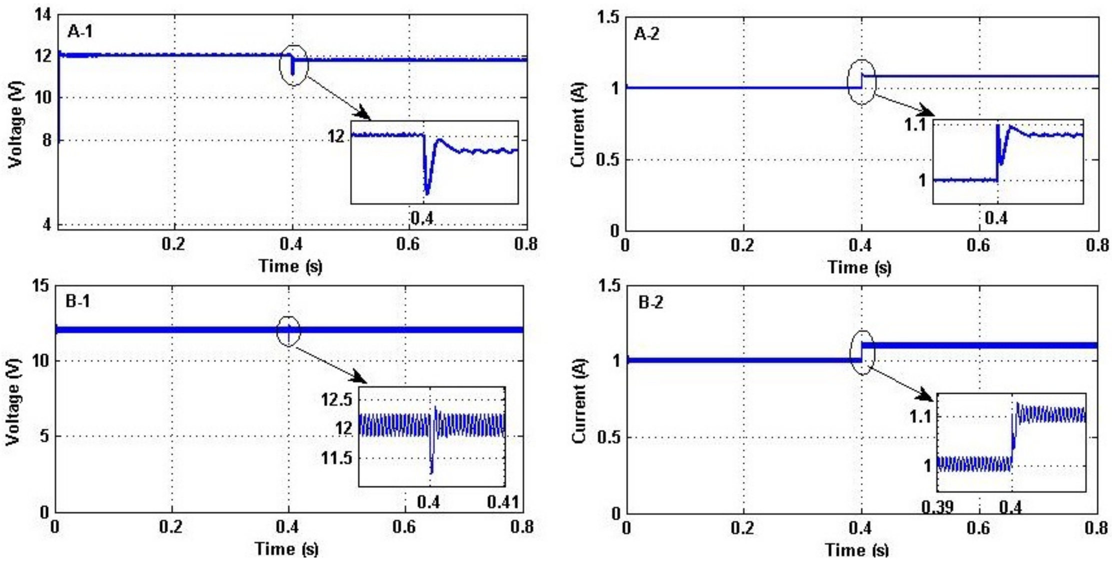


Fig. 5 Simulation results of the Output voltage response (A-1) and the output load current response (A-2) using PWM-based SMC (A); Simulation results of the Output voltage response (B-1) and the output load current response (B-2) using HM-based SMC (B), both with an output load variation

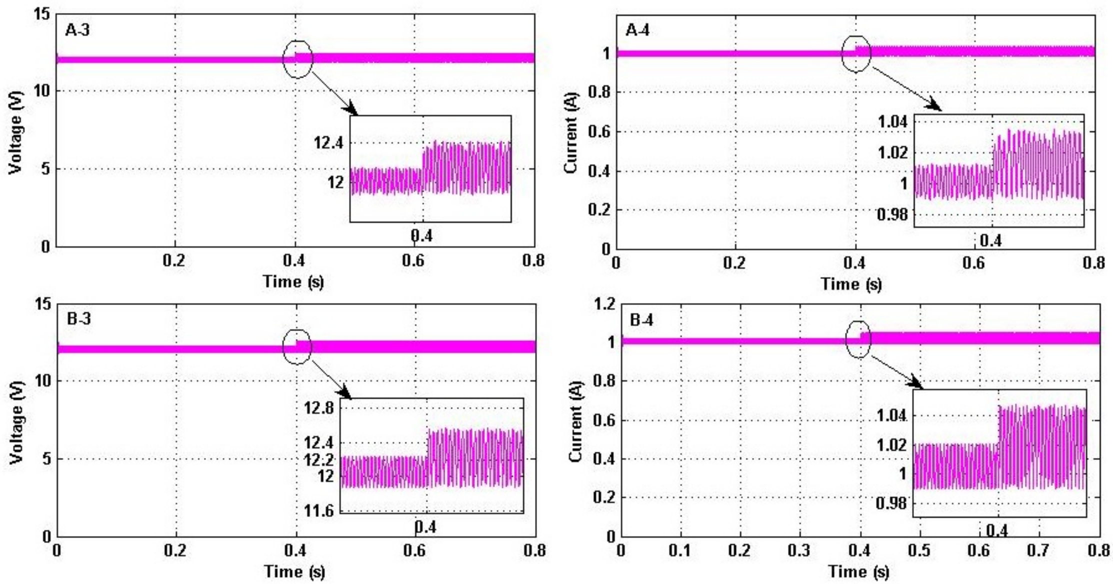


Fig. 6 Simulation results of the Output voltage response (A-3) and the output load current response (A-4) using PWM-based SMC (A); Simulation results of the Output voltage response (B-3) and the output load current response (B-4) using HM-based SMC (B), both with an input voltage variation

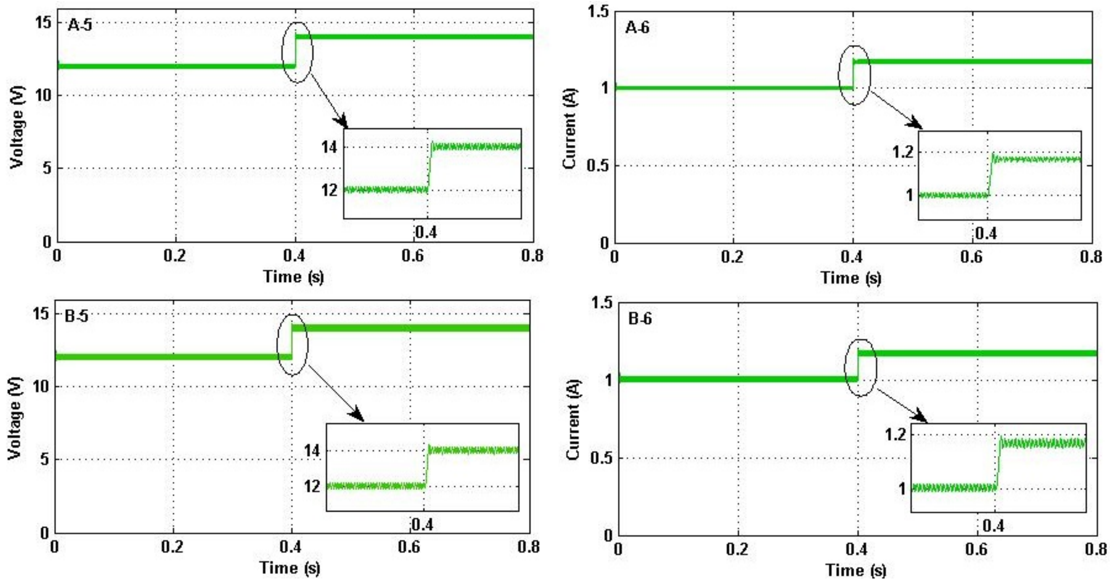


Fig. 7 Simulation results of the Output voltage response (A-5) and the output load current response (A-6) using PWM-based SMC (A); Simulation results of the Output voltage response (B-5) and the output load current response (B-6) using HM-based SMC (B), both with a reference voltage variation

Finally, the robustness test versus the power reference value changes is illustrated in Fig. 7. Indeed, at t = 0.4 s, $V_{ref}$ is slightly changed from 12V to 14V.

The difference between PWM-based SMC and HM-based SMC in terms of stability assessment and performance analysis under system parameters variation are recapitulated in Table II. According to these results, it can be noticed that the two control strategies objective is fulfilled and the performances are satisfactory. They reject controlled system parameter variations with a quiet difference.

TABLE II
COMPARATIVE PERFORMANCES OF PWM-BASED SMC WITH HM-BASED SMC

| | PWM-based SMC | HM-based SMC |
|---|---|---|
| | **Load variation** | |
| *Time of compensation* | *0.0003 s* | 0.001 s |
| *The drop width* | *0.229 V* | 0.649 V |
| *Amplitude of oscillations* | *0.15 V* | 0.25 V |
| *Response time* | *0.002 s* | 0.002 s |
| | **Input variation** | |
| *Amplitude of oscillations* | | |
| *For t < 0.4 s* | *0.15 V* | *0.24 V* |
| *For t > 0.4 s* | ↑ *0.26 V* | ↑ *0.3 V* |
| | **Reference variation** | |
| *Time of transition* | *0.0007 s* | *0.0006 s* |
| *Amplitude of oscillations* | *0.15 V* | *0.24 V* |

## V. CONCLUSION

The fixed-frequency PWM-based controller is a translated form of the HM-based controller; these techniques have improved the dynamic behavior and they are able to cope with input voltage and load variations, as well as provide stability in any operating conditions.

The method used in nonlinear PWM controller design is to assume a large signal average model of the converter at the start of the derivation. Furthermore, the adoption of a fixed-frequency PWM technique in the SM controller provides, in a comparative way, better steady-state stability and output voltage regulated converter. Furthermore, the dynamic responses of the PWM-based SMC and HM-based SMC that both are operating at a similar constant switching frequency do not differ significantly. Recall that in a nonlinear SM-controlled system, the dynamic behavior is mainly determined by the sliding coefficients. For both types of control techniques, the dynamic responses are similar, because they have the same set of sliding coefficients and are operating in the same switching frequency.

The carried-out simulations show very promising results in terms of reference tracking performances and robustness. They prove the appropriateness of SM control for such kind of system.

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**Rihab Hamdi** (Tunisia, 1993), Ph.D. student in Electrical Engineering at the University of Biskra, Algeria and graduated as Energy Engineer in 2017 from the National Engineering School of Monastir, Tunisia. She then joined the research group of Prof. Mebark Bahri at the Energetic Systems Modelling Laboratory (LMSE), University of Biskra, Algeria and supervised by Prof. Amel Hadri Hamida in a research project titled: “Controlling a Multicellular Converter for an Electric Vehicle Application”.

**Amel Hadri Hamida** (Algeria, 1979), Professor in Electrical Engineering. She received the Engineer, the “Magistère” and the “Doctorat en sciences” degrees in electrical engineering from the University of Biskra, Algeria in 2002, 2005 and 2011 respectively. Pr. Hadri-Hamida is an associate professor with the University of Biskra-Algeria and a member of the LMSE Laboratory.

**Ouafae Bennis** Lecturer at PRISME Institute. She received the Ph.D. at Paul Sabatier University in Toulouse, France in 1982, research engineer until 1992, lecturer at the University of Orleans, France since.