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On two control strategies for multicellular converters

Salwa BEN SAID, Kamel BEN SAAD , and Mohamed BENREJEB,
Université EL MANAR, Ecole Nationale d'Ingénieurs de Tunis
BP 37, le Belvédère, Tunis 1002, TUNISIA,
e-mail: bensaid.salwa@yahoo.fr, kamel.bensaad@enit.rnu.tn, mohamed.benrejeb@enit.rnu.tn

***Abstract*—In this paper, two control strategies are proposed for multicellular converters. The first one is a proportional integral control which is applied after a feedback linearization of the studied converter model. The second one is a sliding mode control characterized by its efficiency for nonlinear systems. The sliding control is based on sliding commutation surfaces defined by Lyapunov functions. Some simulations are carried out to prove the efficiency and the robustness of the two proposed controls for the case of a three cells converter.**

***Index Terms*—multicellular converter, feedback linearization, PI, sliding mode, robustness.**

I. Introduction

POWER electronics knew important technological developments thanks to the improvements of semiconductors, power components and systems of energy conversion. Among these systems, multicellular converters, which are built upon a series-association of elementary commutation cells, are more and more used in industrial applications. Indeed, they are characterized by their modularity and high efficiency. However, the major drawback of this kind of converter is their control complexity.

Modeling is a very important step for control law design and synthesis. In the literature, several approaches have been considered to develop models for multicellular converter. Initially, models have been developed to describe their instantaneous, harmonic or averaging behaviors [6][5][1].

The converter model must be adequately simple to allow the control synthesis and enough precise to achieve the desired behavior. Because it is based on continuous and discrete variables, multicellular converter modeling is claimed to be difficult [7] [8]. According to previous studies, three kinds of models are developed.

The average model consists into calculating average values of all variables during one sampling period. Nevertheless, this model cannot represent the capacitors terminal voltage natural balancing. The harmonic model consists into the calculation of the voltage harmonic phases and amplitudes by considering the charging current in steady-state operation. The instantaneous model deals with time-evolution of all variables including the switch states (discrete location). This model makes controllers design difficult because the converter is not a continuous system but a mixture of continuous and discrete systems [2][3].

The natural control technique of a multicellular converter is performed in open loop which is simple to apply. But to insure the robustness of the considered converter, it is necessary to use a closed loop control that takes into account the evolution of the capacitor voltages [2].

The aim of this paper is to propose two control strategies for multicellular converters. The first control law, which is a Proportional Integral (PI) control, is based on the feedback linearization of the nonlinear studied converter model. The second control law is a sliding mode control which deals directly with the nonlinear multicellular model.

This paper is organized as follows: Section 2 presents the studied multicellular converter model. In section 3, the proposed PI control is presented and tested. Section 4 describes the proposed sliding mode controller.

II. Studied multicellular general model description

The general structure of the studied multicellular converter is presented in figure 1. It is composed of p-cells. Each cell contains two complementary power electronic components controlled by a binary switch. That means that if the upper switch of the k^{th} cell is closed $u_k = 1$ and the lower switch is open.

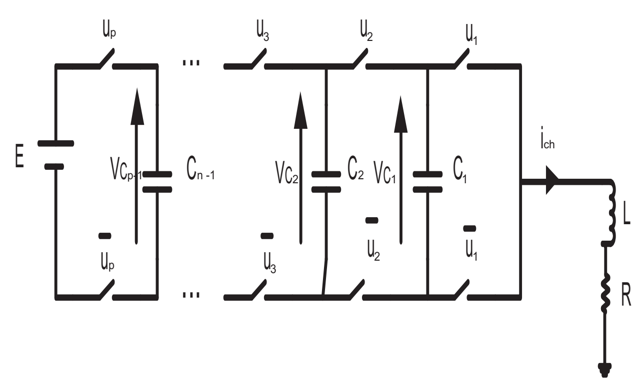

Fig. 1. Studied p-cells converter.

The multicellular converter cells are associated in series with a RL load and the cells are separated by capacitors that can be considered as continuous voltage sources [1][10]. Thus, the converter has $p - 1$ floating voltage sources.

In order to ensure normal operations, it is necessary to guarantee a balanced distribution of the floating voltages $V_{c_k} = k\frac{E}{p}$. The output voltage V_s can attend p voltage levels $\left(\frac{E}{p}, ..., (p-1)\frac{E}{p}, E\right)$[10].
The general state space representation of the p-cells converter is given by the system (1):

$$\begin{cases} \frac{dV_{C_1}}{dt} = \frac{1}{C_1}(u_2 - u_1)\, i_{ch} \\ \vdots \\ \frac{dV_{C_{p-1}}}{dt} = \frac{1}{C_{p-1}}(u_p - u_{p-1})\, i_{ch} \\ \frac{di_{ch}}{dt} = -(u_2 - u_1)\frac{V_{C_1}}{L} - (u_3 - u_2)\frac{V_{C_2}}{L} - \\ ... - (u_p - u_{p-1})\frac{V_{C_{p-1}}}{L} - \frac{R}{L} i_{ch} + u_p \frac{E}{L} \end{cases} \tag{1}$$

For this model the load current i_{ch} and the floating voltages V_{C_k} are used as space variables such that [7]:

$$\dot{X} = AX + B(X)u \tag{2}$$

where $X = [V_{C_1}, V_{C_2}, .., V_{C_p}, i_{ch}]^T$ is the continuous state vector and $u = [u_1, ...u_p]^T$ the applied control input. With u_i the control duty cycle of the i^{th} switch
The state matrix A is defined as follows :

$$A = \begin{pmatrix} 0 & \cdots & 0 & 0 \\ \vdots & \ddots & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & -\frac{R}{L} \end{pmatrix} \tag{3}$$

and the control matrix B is given by the following expression :

$$B = \begin{bmatrix} -\frac{i_{ch}}{C_1} & \frac{i_{ch}}{C_1} & 0 & ... & 0 \\ 0 & -\frac{i_{ch}}{C_2} & \frac{i_{ch}}{C_2} & ... & 0 \\ .. & 0 & .. & .. & .. \\ 0 & ... & 0 & -\frac{i_{ch}}{C_{p-1}} & \frac{i_{ch}}{C_{p-1}} \\ \frac{V_{C_1}}{L} & \frac{V_{C_2} - V_{C_1}}{L} & ... & \frac{V_{C_{p-1}} - V_{C_{p-2}}}{L} & \frac{E - V_{C_{p-1}}}{L} \end{bmatrix} \tag{4}$$

III. PI CONTROL OF A MULTICELLULAR CONVERTER

The main objective of the proposed PI control law is to regulate the output current and all voltages across the flying capacitors.

As the studied multicellular converter is nonlinear, we propose in the following the application of the feedback linearization technique.

A. Multicell converter feedback linearization

In order to linearize the mathematical system (2) we define the control input u as follows:

$$u = -FX + Le \tag{5}$$

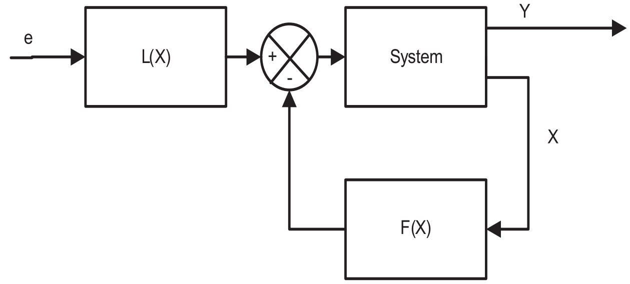

Fig. 2. Multicellular converter feedback linearization

Figure 2 describes the feedback linearization principal of the studied system with the definition of the new input vector e.

Thus, the state space representation is transformed into the following equation:

$$\dot{X} = (A - BF)X + BLe \tag{6}$$

Let A_d and B_d be the desired state space and control matrix defined as follows:

$$A_d = (A - BF) \tag{7}$$

$$B_d = BL \tag{8}$$

Let us assume that A_d and B_d has the following forms:

$$A_d = \begin{pmatrix} -\lambda_1 & 0 & \cdots & 0 \\ 0 & -\lambda_2 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & -\lambda_n \end{pmatrix} \tag{9}$$

and

$$B_d = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{pmatrix} \tag{10}$$

F and L matrix are obtained by:

$$F = B^{-1}(A - A_d) \tag{11}$$

$$L = B^{-1}B_d \tag{12}$$

To apply the described approach, the matrix B must be inversible. Thus, we demonstrated that:

$$\det B(X) = \frac{i_{ch}^{n-1}}{C_1 C_2 \ldots C_{n-1}} \frac{E}{L} \tag{13}$$

For the proposed feedback linearization, we consider the case of a 3 cells converter connected to an RL load, figure 3.

This converter can be modeled by the state space representation defined by equation 2,
where $A = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{R}{L} \end{pmatrix}$

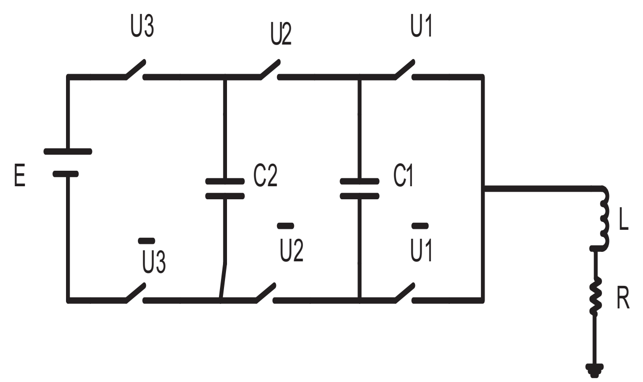

Fig. 3. Studied three-cell converter.

and $B = \begin{pmatrix} -\frac{i_{ch}}{C_1} & \frac{i_{ch}}{C_1} & 0 \\ 0 & -\frac{i_{ch}}{C_2} & \frac{i_{ch}}{C_2} \\ \frac{V_{c_1}}{L} & \frac{V_{c_2}-V_{c_1}}{L} & \frac{E-V_{c_3}}{L} \end{pmatrix}$

We fixed the desired matrix A_d and B_d as :

$$A_d = \begin{pmatrix} -\lambda_1 & 0 & 0 \\ 0 & -\lambda_2 & 0 \\ 0 & 0 & -\lambda_3 \end{pmatrix} \quad (14)$$

$$B_d = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (15)$$

Thus, we can deduce the expression of F and L :

$$F = \begin{pmatrix} \frac{-C_1\lambda_1(E-V_{c_1})}{Ei_L} & \frac{-C_2\lambda_2(E-V_{c_2})}{Ei_L} & L\left(\frac{\lambda_3-\frac{R}{L}}{E}\right) \\ \frac{C_1\lambda_1 V_{c_1}}{Ei_L} & \frac{-C_2\lambda_2(E-V_{c_2})}{Ei_L} & L\left(\frac{\lambda_3-\frac{R}{L}}{E}\right) \\ \frac{C_1\lambda_1 V_{c_1}}{Ei_L} & \frac{C_2\lambda_2 V_{c_2}}{Ei_L} & L\left(\frac{\lambda_3-\frac{R}{L}}{E}\right) \end{pmatrix} \quad (16)$$

$$L = \begin{pmatrix} \frac{-C_1(E-V_{c_1})}{Ei_L} & \frac{-C_2(E-V_{c_2})}{Ei_L} & \frac{L}{E} \\ \frac{C_1 V_{c_1}}{Ei_L} & \frac{-C_2(E-V_{c_2})}{Ei_L} & \frac{L}{E} \\ \frac{C_1 V_{c_1}}{Ei_L} & \frac{C_2 V_{c_2}}{Ei_L} & \frac{L}{E} \end{pmatrix} \quad (17)$$

Let us denote $\lambda_1 = \frac{Ei_L}{C_1}$, $\lambda_2 = \frac{Ei_L}{C_2}$ and $\lambda_3 = \frac{R}{L}$
So, we can write the expression of F as:

$$F = \begin{pmatrix} V_{c_1} - E & V_{c_2} - E & 0 \\ V_{c_1} & V_{c_2} - E & 0 \\ V_{c_1} & V_{c_2} & 0 \end{pmatrix} \quad (18)$$

B. Integral Proportional Regulation

The feedback linearization leads to a linear system. We propose in the following to apply a PI regulator as shown in Figure 4.

The parameters of the studied converter are given in table I.

Figures 5 and 6 show respectively the floating voltages and the load current i_{ch} evolutions.
The imposed test cycle is as follows:

- $t = 0ms$, $I_{ref} = 100A$;
- $t = 10ms$, $I_{ref} = 80A$;
- $t = 30ms$, $I_{ref} = 120A$;

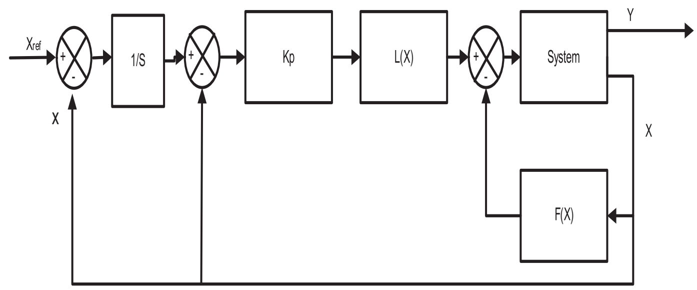

Fig. 4. Schema bloc of regulation loop with PI regulator.

TABLE I
STUDIED MULTICELL CONVERTER PARAMETERS

Components	Rating values
E	$1500V$
L	$1mH$
$C1, C2$	$40\mu F$
R	10Ω

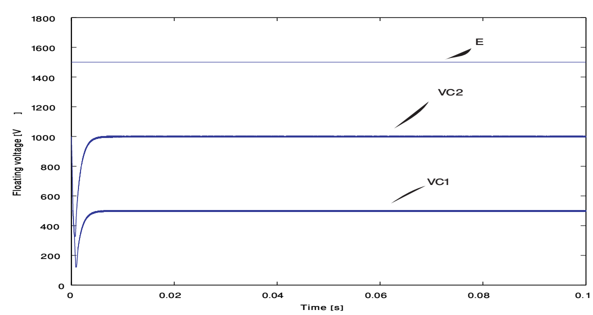

Fig. 5. Floating voltage V_{C_1} ,V_{C_2} and E evolutions

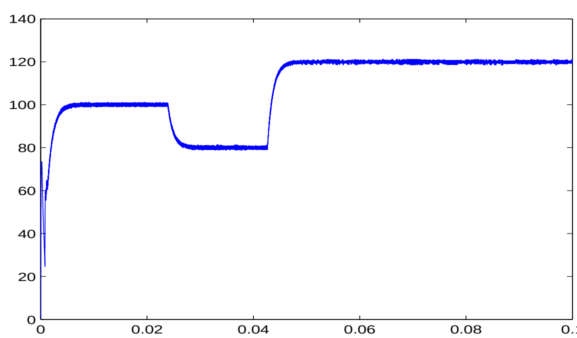

Fig. 6. Load current i_{ch} evolution

From the simulation results it is clear that the capacitor voltages and the output current reach the desired reference values without static errors.
To test the robustness of the proposed control we consider the variation of the input voltage and the load resistance, for the case of an input variation according to the following sequences:

- $t = 0ms$, $E = 1500V$;
- $t = 10ms$, $E = 1300V$;

- $t = 30ms$, $E = 1800V$;

The obtained simulation results are given in figures 7 and 8.

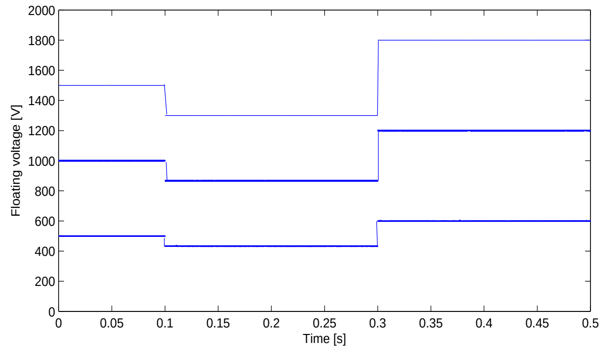

Fig. 7. Floating voltage V_{C_1} , V_{C_2} and E evolutions

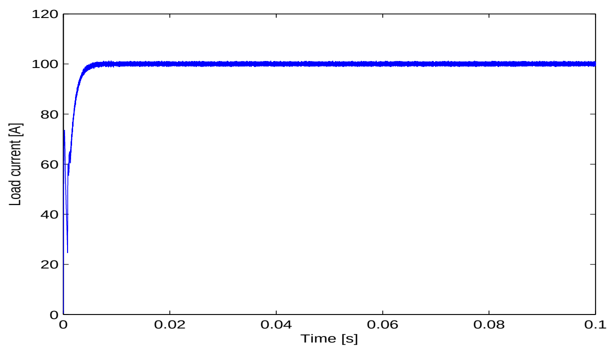

Fig. 8. Load current i_{ch} evolution

The robustness test of the proposed control law was considered for the case of the load resistance variation. At $t = 20ms$ the load resistance became twice its initial value.The obtained simulation results are given by figures 9 and 10.

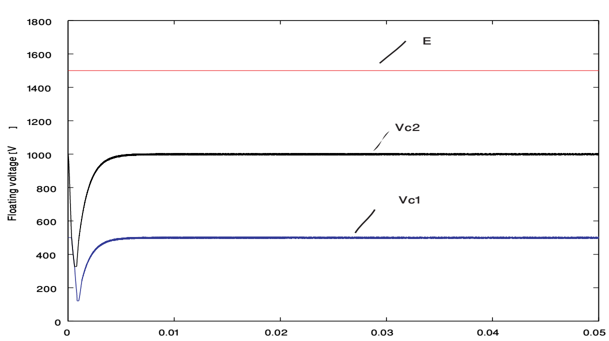

Fig. 9. Floating voltage V_{C_1} , V_{C_2} and E evolutions

From these simulation results, we can deduce that the proposed control law is suitable for the studied converter.

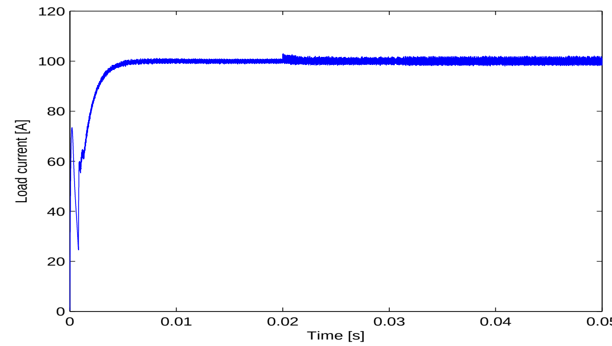

Fig. 10. Load current i_{ch} evolution for variation of load

Moreover, it rejects external perturbations and some controlled system parameters variations.
Thus, we can confirm that the proposed control is robust for the considered load variation.

IV. Proposed sliding mode control for multicell converter

Sliding mode control is suitable control solution for switching converter. We propose in this section a sliding mode controller for the studied multicellular converter.
Sliding mode control is a nonlinear control technique based on variable structure theory. It is very simple to complement and gives the controlled system robustness and good dynamical response.
For the proposed sliding mode control, we define the sliding surface defined as follows:

$$S = \begin{pmatrix} S_1 \\ \vdots \\ S_p \end{pmatrix} \quad (19)$$

The component S_i are defined as follows:

$$\begin{cases} S_1 = (V_{ref_1} - V_{C_1})I_{ref} \\ S_2 = (V_{ref_2} - V_{C_2})I_{ref} \\ \vdots \\ S_{p-1} = (V_{ref_{p-1}} - V_{C_{p-1}})I_{ref} \\ S_p = (I_{ref} - i_{ch})E \end{cases} \quad (20)$$

where V_{C_k} is the flotting voltage of the k^{th} capacitor and V_{ref_k} the reference voltage defined by the following equation 21:

$$V_{ref_k} = k\frac{E}{p} \quad (21)$$

with $k = 1...(p-1)$.
i_{ch} is the load current and I_{ref} the desired reference of load current.

The control signals are defined as follows:

$$u_k = \frac{1}{2}(1 + sign(S_i)) \tag{22}$$

with $k = 1...p$.

This control aims to allow the convergence of the voltages V_{c_i} and the current i_{ch} to their reference values.

In order to illustrate the performance of the proposed control, we considered the case of a three-cell converter connected to an RL load presented in section 3.

The parameters of the studied converter are given in table I.

Figures 11 and 12 show respectively the floating voltages V_{C_1} , V_{C_2} and the load current i_{ch} evolutions.

The floating voltages are set around their references.
The imposed test cycle is as follows:

- $t = 0ms$, $I_{ref} = 100A$;
- $t = 10ms$, $I_{ref} = 80A$;
- $t = 30ms$, $I_{ref} = 120A$;

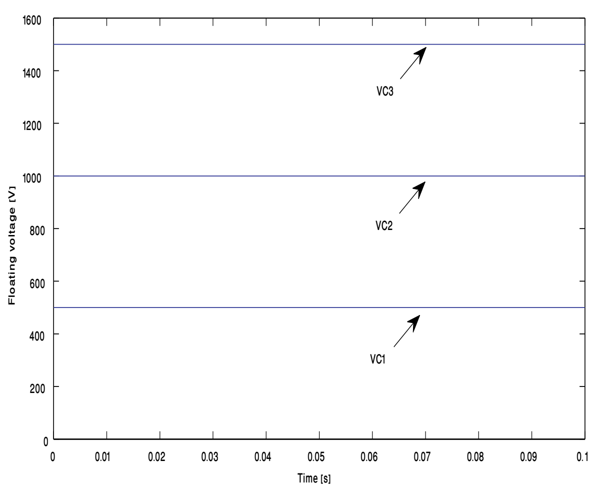

Fig. 11. Floating voltage V_{C_1} and V_{C_2} evolutions obtained by application of the sliding mode control

We can notice that, the load current reaches the desired references.

To test the robustness of the proposed control, we consider the variation of the input voltage and the load resistance.
For the case of the input voltage variations, we applied, the following test sequence:

- $t = 0ms$, $E = 1500V$;
- $t = 10ms$, $E = 1300V$;
- $t = 30ms$, $E = 1800V$;

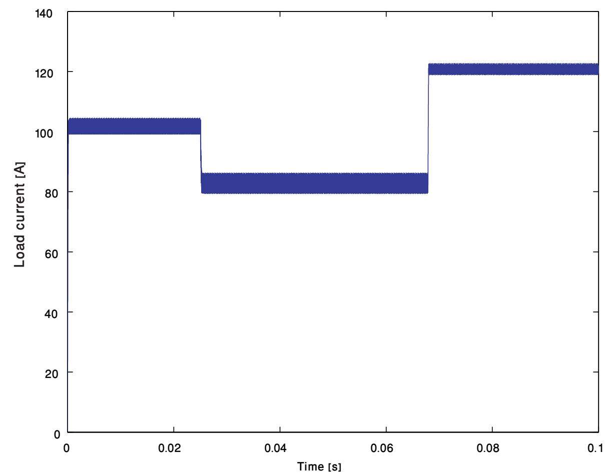

Fig. 12. Load current i_{ch} evolution obtained by application of the sliding mode control

The obtained simulation results are given in figures 13 and 14.

We can notice that the control keeps the load current constant at the desired I_{ref} value and the floating voltages change with the variation of the input voltage.

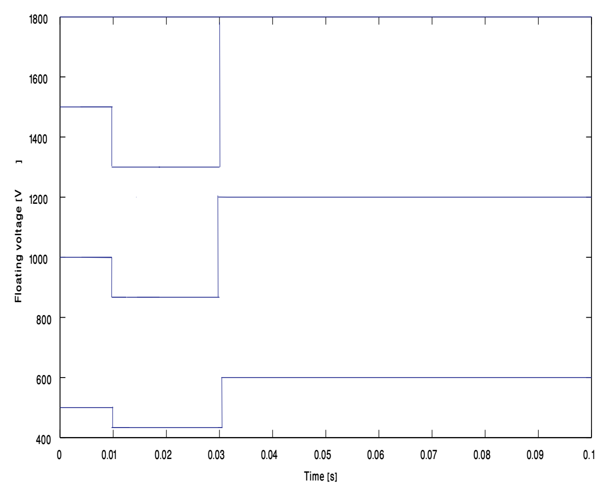

Fig. 13. Floating voltages V_{C_1} and V_{C_2} evolutions under variation of current reference

Figure 15 and 16 presents the voltages V_{C_1},V_{C_2} and the load current for a load resistance change from 10Ω to 15Ω at $t = 0.2s$.

According to the obtained results, it can be noticed that the performances of the proposed control for load variation are satisfactory.

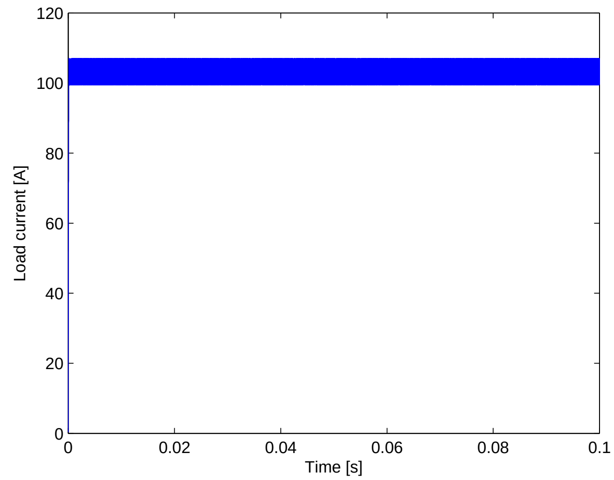

Fig. 14. Load current i_{ch} under variation of current reference

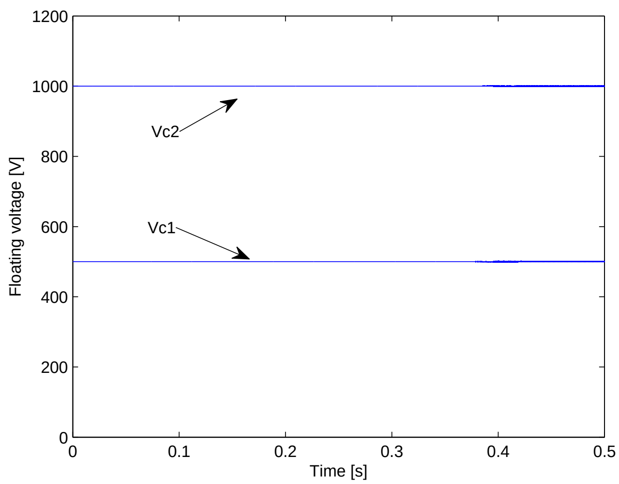

Fig. 15. Floating voltages V_{C_1} and V_{C_2} for a load resistance change

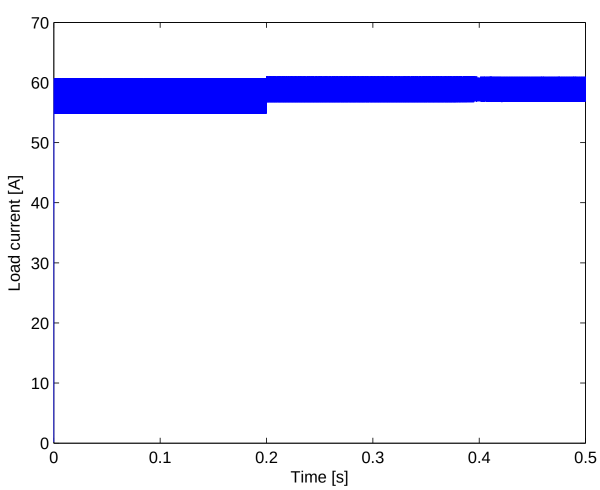

Fig. 16. Load current i_{ch} evolution for a load resistance change

V. CONCLUSION

In this paper, two closed loop control strategies are proposed for a multicellular converter. This kind of converter is more and more used for several industrial applications thanks to its simple architecture.

The first proposed control is based on a PI regulator. The design of this control was performed after a feedback linearization of the studied multicellular converter. The simulation results of the proposed PI control show the efficiency and the robustness of this control law.

The second proposed control is based on a sliding mode control which is adequate for switching converters.
The design of the proposed sliding mode control is based directly on the nonlinear studied converter model. The simulation results prove the efficiency and the robustness of the designed sliding mode control. As a comparison between the two proposed controls, we can notice that the transient response duration obtained by application of the SMC is less than the one obtained by PI control.

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