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Comparison of Sliding Mode and Petri Nets Control for Multicellular Chopper

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Abstract: In this paper a new class of power converters, serial multicellular chopper, will be studied. After recalling the dynamical equations of the converter, its hybrid dynamical behavior and properties are highlighted. This hybrid system induces new and difficult control problems. Then, two control strategies are proposed. The first is a sliding mode control and the second is a Petri Nets control. Some simulations are carried out to prove the efficiency and the robustness of the two controls for the case of a two cells converter connected to a nonlinear load. The comparison between sliding mode control and Petri nets control is carried out. Simulation results are provided to verify the conclusions.

Keywords: Multicellular chopper; Sliding mode control; Petri nets control; Hybrid dynamic systems

1 Introduction

The field of power electronics has seen some important developments in the last two decades. The design and manufacturing process of power components has improved drastically, allowing for new structures for energy conversion to be possible. The approach of multicell structures is relatively new. The idea was introduced in the 1990s [1, 2] and it proposed a series of commutation cells linked by floating voltage sources. These floating voltage sources are implemented by using capacitors. In this way, we can have N voltage levels with $p = N - 1$ commutation cells (Fig. 1). The floating voltage sources set a voltage drop for each cell equal to $\frac{E}{p}$, while the value of the current through the switches is identical with that of a classical structure [3]. Because of the use of capacitors as floating voltage sources, the voltage across them must be balanced within a certain interval around the desired value of $\frac{E}{p}$. The ideal way to do this is without any sensors to measure the capacitor voltages. So we need to be able to determine the capacitor voltages only by measuring the output current of the system [4, 5].

The research in this area offers a wide variety of approaches. The aim of this paper is to propose two control strategies for multicellular converters. The first control law is a sliding mode control. The second control law is a Petri nets control which deals directly with the nonlinear multicellular model. The performance of these controls are demonstrated for a two cell chopper connected to a nonlinear load.

The paper is organized as follows: Section II, the multicellular chopper modeling and analysis of a switching cell are presented. In Section III the direct control based on sliding mode techniques is presented. This methods is allows to the two cells chopper associated to a nonlinear load. Section IV is devoted to the Petri net control of the converter. To illustrate the theoretical results, simulation results are presented in Section V. Finally, a conclusion will be presented in Section VI.

2 Description of the multicellular converter

The multicellular converter is a variable structure system whose configuration changes during operation. The multicellular converter consists of cells (Fig. 1). Each cell contains two complementary power electronics components and it can be

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controlled by a binary switch u_k. This signal u_k is equal to 1 when the upper switch of the cell is conducting and 0 when the lower complementary switch of the cell is conducting. These cells are associated in series with R, L load and separated by capacities that can be considered as continuous sources to these cells. The converter has $p - 1$ floating voltage sources. In order to ensure a normal functioning, it is necessary to guaranty a regulated distribution of the voltages v_{C_k} to their equilibrium values that equal to $k\frac{E}{p}$ [6].
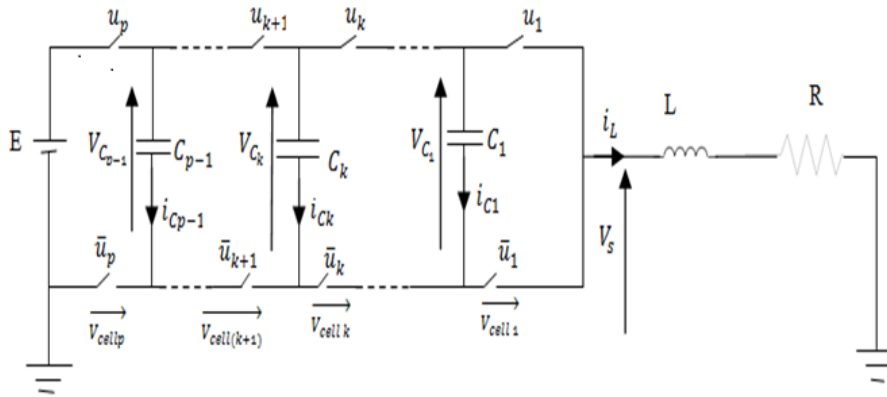

Figure 1: P-cells chopper connected to RL load

The output voltage V_s possesses p voltage levels $(0, \frac{E}{p}, \frac{(p-1)}{p}, E)$ [7]. The model of this system can be obtained and represented by p differential equations (system 1) giving its state space representation with floating voltages v_{C_k} and load current i_L as state variables.

$$
\begin{cases}
\frac{dv_{C_1}}{dt} &= \frac{u_2 - u_1}{C_1} i_L \\[2mm]
\frac{dv_{C_2}}{dt} &= \frac{u_3 - u_2}{C_2} i_L \\[2mm]
&\cdots \\[2mm]
\frac{dv_{C_{p-1}}}{dt} &= \frac{u_p - u_{p-1}}{C_{p-1}} i_L \\[2mm]
\frac{di_L}{dt} &= \frac{u_1 - u_2}{L} v_{C_1} + \frac{u_2 - u_3}{L} v_{C_2} + \ldots \\[2mm]
&\quad + \frac{u_{p-1} - u_p}{L} v_{C_{p-1}} + \frac{u_p}{L} E - \frac{R}{L} i_L
\end{cases}
\tag{1}
$$

To simplify the study and the notations, we will study the overlapping operation of a converter with two cells (Fig. 2). Its function is to supply a passive load (RL) in series with another nonlinear load connected in parallel with a capacitor [8].

Four operating modes are then possible as shown in Fig. 3. Note that the floating source takes part in the evolution of the dynamics of the system only to the third and fourth mode. In the third mode, the capacity discharges and charge during the fourth mode. Thus, if these two modes last same time with a constant charging current, then the average power transmitted by this floating source over one period of commutation is null. We also notice that these two modes make it possible to obtain by commuting the additional level $\frac{E}{2}$ on the output voltage V_s.

As the switches of each cell are regarded as ideals, their behavior can be modeled by a discrete state taking of the values 0 (on) or 1 (off). In practice, some of these states never will be visited for reasons of safety measures or following the strategy of order adopted or because of the structure of the converter him finally to even or comply with the rule of adjacency. The transitions are not necessarily controlled.

The system model can be represented by three differential equations giving its state space.
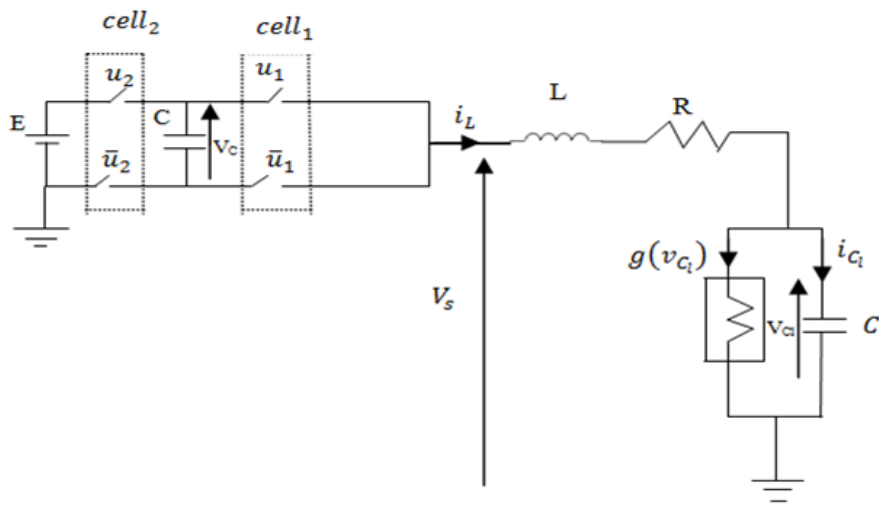
Figure 2: Two-cells chopper connected to a nonlinear load

$$\begin{cases} L\frac{di_L}{dt} &= (u_1 - u_2)v_C - v_{C_l} - Ri_L + u_2 E \\ \\ C\frac{dv_C}{dt} &= (u_2 - u_1)i_L \\ \\ C_l\frac{dv_{C_l}}{dt} &= i_L - g(v_{C_l}) \end{cases} \qquad (2)$$

where $g(v_{C_l}) = G_b v_{C_l} + \frac{1}{2}(G_a - G_b)(|v_{C_l} + 1| - |v_{C_l} - 1|)$, which is the mathematical representation of the characteristic curve of nonlinear load.

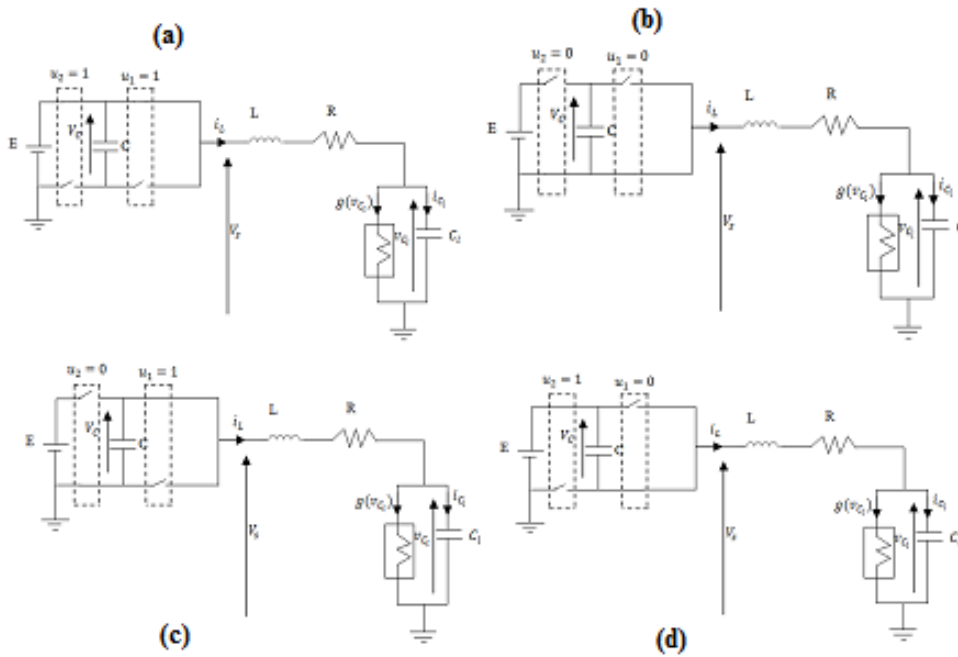The slopes of the inner and outer regions are G_a and G_b.

Figure 3: Switching cell and its configurations

3   Sliding Modes Control Law Synthesis

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 [9–14]. Sliding mode control become more and more attractive to control for multi-cell converter [14]. For this study, we propose to generalize this control approach to p cells multicellular converter. Thus, we define p sliding surfaces as follows (system 4):

$$
\begin{cases}
S_1 & = \quad i_{Lref} v_{C_1} - i_L v_{C_{ref1}} \\[2mm]
S_2 & = \quad i_{Lref} v_{C_2} - i_L v_{C_{ref2}} \\[2mm]
\dots \\[1mm]
S_p & = \quad i_{Lref}(E - v_{C_1}) + i_{Lref}(E - v_{C2}) + \dots + i_{Lref}(E - v_{Cp-1}) \\[2mm]
& \quad\quad -i_L(v_{Cref1} + v_{Cref2} + \dots + v_{Crefp-1})
\end{cases}
\tag{3}
$$

where $e = (i_{Lref} - i_L, v_{Cref1} - v_{C1}, v_{Cref2} - v_{C2}, \dots, v_{Crefp-1} - v_{Cp-1})$.
The tracking error is asymptotically stable. First, we define the control objective which to satisfy the sliding surfaces S as follow (system 5):

$$
\begin{cases}
S_1 & = \quad 0 \\[2mm]
S_2 & = \quad 0 \\[2mm]
\dots \\[1mm]
S_p & = \quad 0
\end{cases}
\tag{4}
$$

And we use the $v_{refk} = k\dfrac{E}{p}$. Next, we get

$$
\begin{cases}
S_1 & = \quad i_{Lref} v_{C1} - i_L v_{Cref1} = 0 \\[2mm]
S_2 & = \quad i_{Lref} v_{C2} - i_L v_{Cref2} = 0 \\[2mm]
\dots \\[1mm]
S_p & = \quad i_{Lref}(E - v_{C1}) + i_{Lref}(E - v_{C2}) + \dots + i_{Lref}(E - v_{Cp-1}) \\[2mm]
& \quad\quad -i_L(v_{Cref1} + v_{Cref2} + \dots + v_{Crefp-1}) = 0
\end{cases}
\tag{5}
$$

We deduce:

$$
\begin{cases}
v_{C1} & = \quad v_{Cref1} \\[2mm]
v_{C2} & = \quad v_{Cref2} \\[2mm]
\dots \\[1mm]
i_L & = \quad i_{Lref}
\end{cases}
\tag{6}
$$

The closed loop control sequences are defined as:

$$
u_i = \frac{1}{2}[1 - sign(S_i)],
\tag{7}
$$

for $i \in \{1, 2, \dots, p\}$. The proposed control approach is based on the use of model developed in [15], to control two C cells converter connected to a nonlinear load.

In order to illustrate the performance of the proposed control, we considered a two C cell converter connected to a nonlinear load. Sliding modes are obviously adopted as the two C cells converter has at least one discrete control variable. Indeed, the converter switches are binary controlled (0 or 1) [13, 16, 17]. Let v_{Cref} and i_{Lref} be the desired references of the output voltage and the load current, respectively. Let us define the tracking error

$$
\Delta x^T = [v_C - v_{Cref} i_L - v_{Lref}],
\tag{8}
$$

where $v_{Cref} = \frac{E}{2}$ satisfies the natural balancing. Consider the following control sequences in closed-loop for the two C cells converter

$$u_i = \frac{1}{2}[1 - sign(S_i)], \tag{9}$$

with $i \in \{1, 2\}$. where the sliding mode surfaces are given by

$$\begin{cases} S_1 & = & i_{Lref}v_C - i_L v_{Cref} \\ \\ S_2 & = & i_{Lref}(E - v_C) - i_L v_{Cref} \end{cases} \tag{10}$$

Then, the tracking error Δx is asymptotically stable. Let us first show that the control objective is satisfied on the sliding surfaces S. If

$$\begin{cases} S_1 & = & 0 \\ \\ S_2 & = & 0 \end{cases} \tag{11}$$

and using $v_{Cref} = \frac{E}{2}$ then we get,

$$\begin{cases} i_{Lref}v_C - i_L v_{Cref} = 0 \\ \\ i_{Lref}(E - v_C) - i_L v_{Cref} = 0 \end{cases} \tag{12}$$

then

$$\begin{cases} v_C & = & v_{Cref} \\ \\ i_L & = & i_{Lref} \end{cases} \tag{13}$$

This is the proof that the surfaces S_1 and S_2 are attractive and invariant. The control aim is to make the switching surfaces converging to the origin, which therefore allow the state variables reaching their references.

4 Hybrid control of serial multicellular converter based on Petri nets

Dynamical systems are usually continuous or discrete or both. Continuous Dynamical Systems (CDS) have variables whose behavior continuous in time (voltage, current, speed, torque ....). They are often modeled by differential equations or transfer functions. For discrete dynamical systems (DDS), the state space is a discrete set of Boolean value [18]. Systems including both continuous and discrete state are called hybrid dynamic systems. In a very simplified one, SDH has two sub sets, a continuous block and a discrete block:

The continuous block is the dynamic evolution of the state continues, in our case the RL connection

The block has the discrete system is discrete event receives internal events, external conditions

In this work, we were interested in modeling method and control systems hybrid event-based dominant the use of Petri nets [19]. The method is illustrated in Figure 4 The control consists of two parts, a continuous and a discrete. The first is based on a classical PI control loop for regulating the output voltage. This loop has as input the error $E_1 = v_{Cref} - v_C$ and i_{Lref} as output a current. The second control loop is done by a Petri net whose mission is the current regulation IS to value i_{Lref} calculated by the PI. The current regulation is followed by a voltage balancing to ensure a better distribution of the latter in each cell. Fig. 5 represents the Petri net control of the switches, the places P_1 and P_2 respectively are modeling the state of the switches of cells $Cell_1$, and $Cell_2$. This algorithm is developed in order to control the system, in case it has an imbalance in the voltage of cells. The transition from one place to another is dependent on the voltage state (Table 3), current i_{Lref} and chopper configurations. The closure of the switch of the cell (Celli) depends on the validation of the transition t_{i0} and the elapsed delay d_i. This delay models the time allowed between two successive commutations, it is based on the technology used for making the switch. For our work we took the same delay ie $d = d_1 = d_2$. In the Petri the role of two arcs inhibitors, is to prevent the presence of more than one, token in places P_1 and P_2. The significance of all places and transition is shown in Table 1 and 2. The imbalance of the cells voltage is one of the major problems of this type of converter, the de-balancing causes a failure of the voltage source if the string current exceeds the current permitted entry. Pollution of the power system harmonics reactions is one of the other consequences of this problem; we will show in the simulation result the contribution of our approach. Most of the converter uses PWM control multiple model for regulating voltage or current, in this work a comparison is made between sliding mode control and Petri nets control.
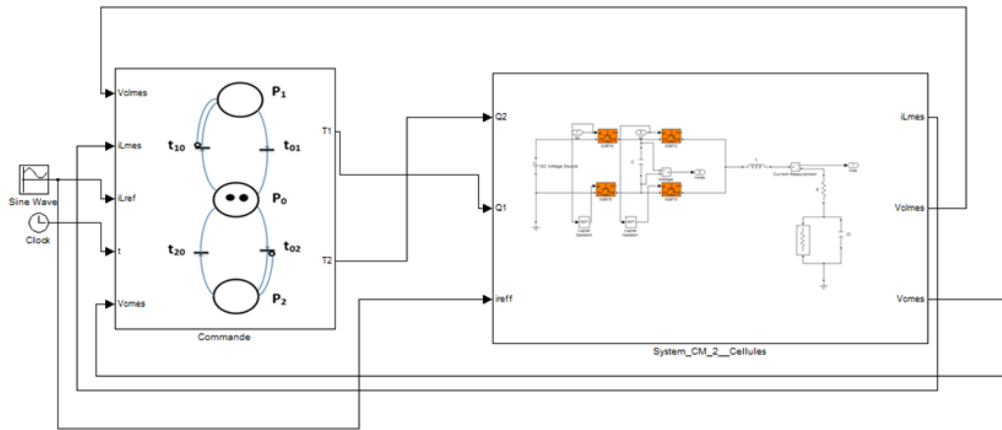
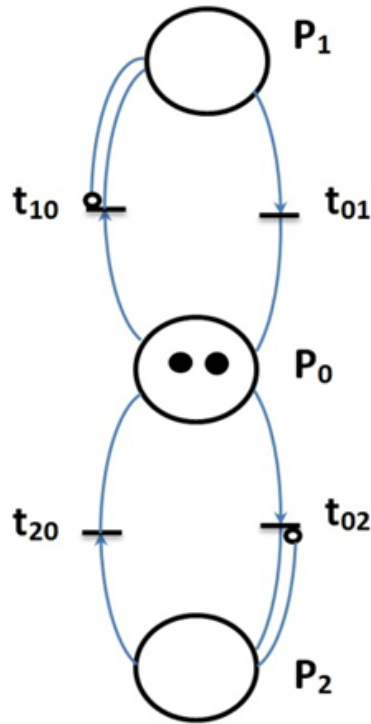Figure 4: Global structure of the Petri net control

Figure 5: Petri net control switches of the converter

Table 1: Signification of places

Places P_i	Designations
P_0	Initial state
P_1	The switch of the first cell
P_2	The switch of the second cell

5 Simulation results

The simulation results are obtained using the parameters of converter as follows: $L = 50mH, C = 0.1\mu F, C_l = 40\mu F, R = 10\Omega, E = 100V, f = 40KHz.$

Table 2: The transitions

Transitions	Designations
t_{01}	$(e \geq +\delta) \, or \, ((-\delta < e < +\delta) \, and \, (v_C > \frac{E}{2}))$
t_{02}	$(e \geq +\delta) \, or \, ((-\delta < e < +\delta) \, and \, (v_C < \frac{E}{2}))$
t_{10}	$(e \leq -\delta) \, or \, ((-\delta < e < +\delta) \, and \, (v_C < \frac{E}{2}))$
t_{20}	$(e \leq -\delta) \, or \, ((-\delta < e < +\delta) \, and \, (v_C > \frac{E}{2}))$

In Petri nets control, PI controller should be redesigned until the stability as well as the dynamic responses satisfy the requirements. But with sliding mode control, PI controller is not required so the design of the closed loop is greatly simplified. Then the floating voltage of the two cells chopper associated to a nonlinear load using sliding mode control and Petri nets techniques are shown in Fig. 6. Figure 7 shows respectively a simulation of the evolution of the load
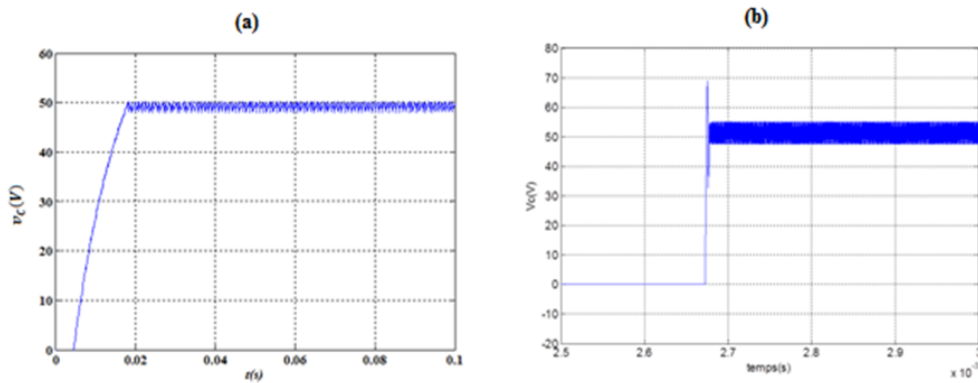

Figure 6: Floating voltage v_C evolutions: (a): sliding mode control; (b): Petri nets control
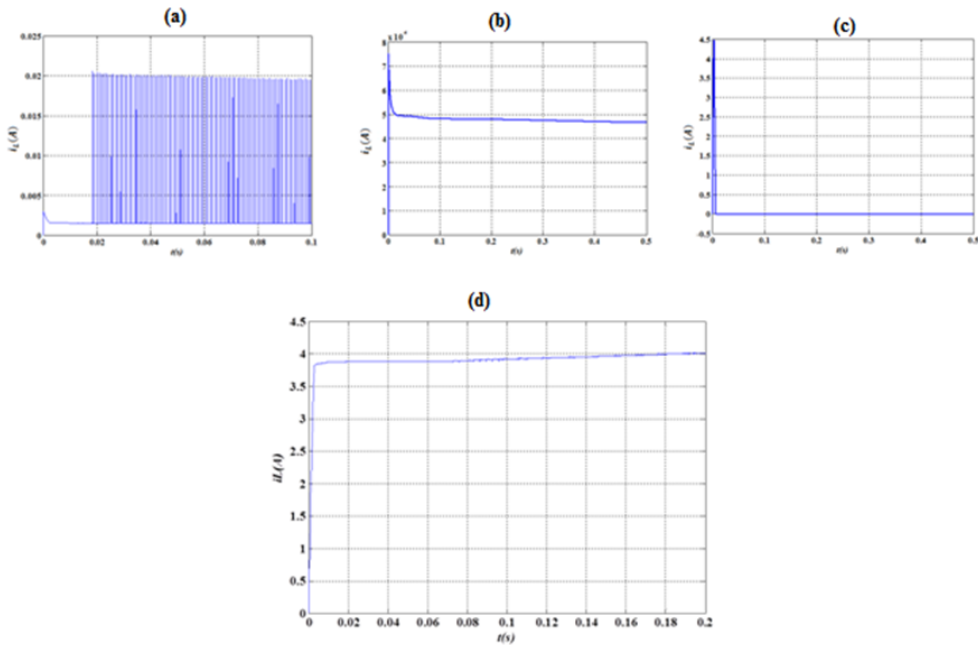

Figure 7: Load current evolutions: (a), (b), (c): sliding mode control ((a): $u_1 = 1$ and $u_2 = 0$ or $u_1 = 0$ and $u_2 = 1$; (b): $u_1 = u_2 = 0$; (c): $u_1 = u_2 = 1$), (d): Petri nets control

currents in the (two cases) control, sliding mode control and Petri nets.

As a comparison between the sliding mode control and the Petri nets controls, we can see that the transient response duration obtained by application of the Petri nets control is less than the one obtained by sliding mode control.

6   Conclusions

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 sliding mode control which is adequate for switching converters. The design of the 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. The second proposed control is based on a Petri nets. This method is based on the statements of floating voltages, the voltage and current reference calculated by the PI and the authorized configurations. Finally simulation results show the convergence of the floating voltage and load current to a neighborhood of the value of the nominal operating voltage and current response times over. As a comparison between the two proposed controls, we can notice that the transient response duration obtained by application of the Petri nets control is less than the one obtained by sliding mode control.

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