NONLINEAR FEEDBACK DECOUPLING CONTROL APPLIED TO STACKED MULTICELLULAR CONVERTER

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In this article we present the stacked multicellular converter, its basic principle and its model. This topology is very interesting provided that the voltage across the floating capacitors remains in balance, which is not the case when the input voltage changes. In this work we propose a control that ensures the rebalancing of the floating voltages and the decoupling of the system. This is the decoupling control with nonlinear feedback. In the end we present the MATLAB/SIMULINK simulation results obtained for 3 ×2 cells stacked multicellular converter controlled by decoupling control with nonlinear feedback used as a chopper.

1. INTRODUCTION

Power electronics has known an important technological development thanks to the development of power semiconductor and new energy conversion systems [1].

Multilevel conversion structures represent a solution to improve the performances given by the classical structures with two voltage levels [2]. A new topology of power converter dedicated to high power applications (up to 50 MW) and medium voltage (DC bus up to 15 kV) called stacked multicellular converter (SMC) was developed and validated within the LEEI laboratory (Laboratoire d'Electrotechnique et d'Electronique Industrielle, Toulouse, France) at the beginning of years 2000. This new hybrid topology enables to share the voltage constraint of the converter on several commutation cells. It also allows splitting the input voltage into several fractions to decrease the rate of the power switches. Compared to competing topologies in this range of application, the SMC converter

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has excellent dynamic performances due the multiplication of the chopped voltage frequency and the increase of the number of levels [3, 4]. Moreover, this topology enables to reduce significantly the energy stored in the floating capacitors by the converter, as well as the losses in the power semiconductors [5].

One of the characteristics of this new topology is to use, as the classical multicellular converter, floating capacitors in order to split the voltage constraint on the power switches. In particular, it is necessary to guarantee that the voltages across those capacitors will be constant during the operation of the converter [6, 7].

So to benefit as much as possible of the significant potential of the stacked multicellular converter, its control must ensure the control of the capacitors voltage and ameliorate the output signal form [8].

Nonlinear feedback decoupling control allows decoupling between the inputs and the system outputs, which will allow us to control the current and the voltage (voltages generated by the floating capacitors) separately, it also allows to stabilize the floating voltages.

This control was proposed by G. Gateau, P. Maussion and T. Meynard for controlling a flying capacitor multicellular converter in an article published in 1997, in J. Phys III France 7, this control has given very good results. From there, we had an idea to apply this control to another configuration of multicellular converter, which is the stacked multicellular converter.

2. STACKED MULTICELLULAR CONVERTER

The stacked multicellular converter (SMC) appeared in the early 2000s; it is constituted of n stacks formed by the series connection of P switching cells separated by $P-1$ floating capacitors.

2.1. BASIC PRINCIPLE OF THE SMC

The SMC converter consists of an hybrid association of commutation cells as presented in Fig. 1 In this particular case, the 2×2 SMC is composed of $P = 2$ columns and $n = 2$ stacks. It uses $P \times n = 4$ commutation cells and $(P-1) \times n = 2$ floating capacitors [5]. We will present the operating principle of the first stack, and it will be the same for the second stack.

It is necessary, during a series association of semiconductor components, to ensure a balanced distribution of the supply voltage on the various switches [9].

If we consider two switches that support a voltage of $E/2$ in the place of one able to support E, it is important to ensure that the voltage applied on these switches was equilibrated at $E/2$. One solution is to insert a voltage source, as indicated in Fig. 1 [9].

If the floating voltage source provides a voltage equal to $E/2$ so the distribution is balanced.

Indeed, $V_{cell11} = E/2$, $V_{cell12} = (E - (E/2)) = E/2$.

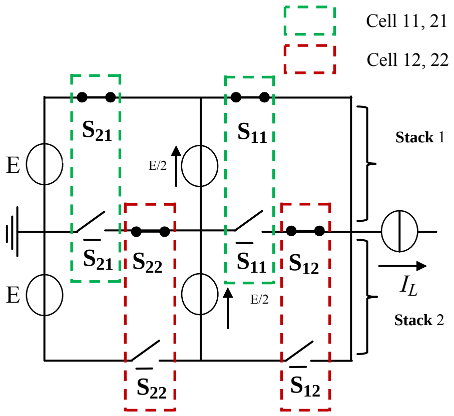


Fig. 1 – A stacked multicellular converter 2×2.

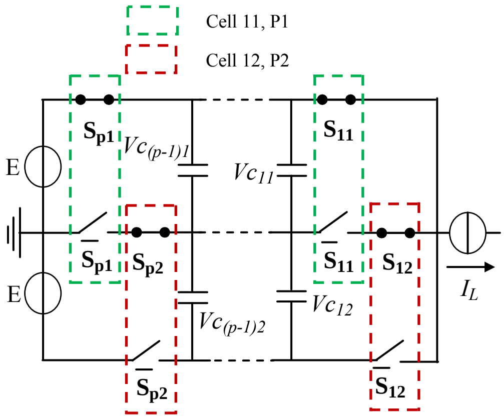


Fig. 2 – A stacked multicellular converter P×2.

This converter type is easily generalizable with P switching cells and 2 stacks (Fig. 2). The converter has P cells and 2 stacks. Each cell is constituted of two switches and a voltage source.

The switches of each stack operate in a complementary manner, when one is conducting the other is blocked. The function of each *cell* i_1 and *cell* i_2 is represented by S_{i1} and S_{i2}.The S_{i1} and S_{i2} will also be called state of the *cell* $_{i1}$ and *cell* $_{i2}$ .The output voltage is noted V_s.

2.2. MODEL OF THE CONVERTER

The assumptions used for the implementation of the model to the average values of a stacked multicellular converter are [9]:

– the switches are ideal (saturation voltage, leakage current, downtime and null switching time).

– the switches of the same commutation cell operate in complementary.

– the values of the floating capacitors C_{i1} and C_{i2} are such that the voltages at their terminals, V_{Ci1} and V_{Ci2} are constants over a cutting period.

– the load current I_L is constant over a cutting period and corresponds to the average value of this one over the same period.

– the supply voltage E is constant.

Equation (1) represents the evolution of the voltage across the floating capacitors (V_{Ci1}, V_{Ci2}) for the two stacks, the evolution of the load current I_L and the difference between the cyclic reports (α_{i1}, α_{i2}); for a stacked multicellular converter used as a chopper powering an R-L load:

$$\begin{cases} \dfrac{\mathrm{d}}{\mathrm{d}t} V_{C_{i1}} = \dfrac{\alpha_{i1}}{C_{i1}} \cdot I_L \\ \dfrac{\mathrm{d}}{\mathrm{d}t} V_{C_{i2}} = \dfrac{\alpha_{i2}}{C_{i2}} \cdot I_L \\ \dfrac{\mathrm{d}}{\mathrm{d}t} I_L = \sum_{i=1}^{P-1} \dfrac{\alpha_{i1}}{L_L} \cdot V_{C_{i1}} + \sum_{i=1}^{P-1} \dfrac{\alpha_{i2}}{L_L} \cdot V_{C_{i2}} + E \cdot \left(\dfrac{u_{p1} + u_{p2}}{L_L} \right) - \dfrac{R_L}{L_L} \cdot I_L \\ \alpha_{i1} = u_{(i+1)1} - u_{i1} \end{cases} . \quad (1)$$

From equations (1) we can define the state equation of this system:

$$\dot{X} = A \cdot X + B(X) \cdot U , \quad (2)$$

where the average values model of the SMC 3×2 is as follows:

$X = \begin{bmatrix} V_{C_{11}} & V_{C_{21}} & I_L & V_{C_{12}} & V_{C_{22}} & I_L \end{bmatrix}^{\mathrm{T}}$, $U = \begin{bmatrix} \alpha_{11} & \alpha_{21} & \alpha_{31} & \alpha_{12} & \alpha_{22} & \alpha_{32} \end{bmatrix}^{\mathrm{T}}$

$$B(X) = \begin{pmatrix} -\dfrac{I_L}{C_{11}} & \dfrac{I_L}{C_{11}} & 0 & 0 & 0 & 0 \\ 0 & -\dfrac{I_L}{C_{21}} & \dfrac{I_L}{C_{21}} & 0 & 0 & 0 \\ \dfrac{V_{C_{11}}}{L_L} & \dfrac{V_{C_{21}} - V_{C_{11}}}{L_L} & \dfrac{E - V_{C_{21}}}{L_L} & \dfrac{V_{C_{12}}}{L_L} & \dfrac{V_{C_{22}} - V_{C_{12}}}{L_L} & \dfrac{E - V_{C_{22}}}{L_L} \\ 0 & 0 & 0 & -\dfrac{I_L}{C_{12}} & \dfrac{I_L}{C_{12}} & 0 \\ 0 & 0 & 0 & 0 & -\dfrac{I_L}{C_{22}} & \dfrac{I_L}{C_{22}} \\ \dfrac{V_{C_{11}}}{L_L} & \dfrac{V_{C_{21}} - V_{C_{11}}}{L_L} & \dfrac{E - V_{C_{21}}}{L_L} & \dfrac{V_{C_{12}}}{L_L} & \dfrac{V_{C_{22}} - V_{C_{12}}}{L_L} & \dfrac{E - V_{C_{22}}}{L_L} \end{pmatrix},$$

$$A = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\dfrac{R_L}{L_L} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\dfrac{R_L}{L_L} \end{pmatrix}.$$

The load current is repeated twice in matrix X, this is because we want to have a square matrix $B(X)$ of size 6×6, which allows us to find the inverse matrix of the matrix $B(X)$ thereafter.

Given that the vector X intervenes in the expression of the matrix $B(X)$ in matrix equation (2), the system is non-linear. Moreover, this matrix is not diagonal. Each component of the input vector α_{i1} and α_{i2} influences on several state variables, and reciprocally, each state variable depends of several components α_{i1} and α_{i2}. For this reason, we can affirm that this system is coupled [10].

3. NONLINEAR FEEDBACK DECOUPLING CONTROL

Nonlinear feedback decoupling control allows the decoupling between the inputs and the system outputs, and stabilize the floating voltages.

From the average values model given by equation (2), it is possible to find a column matrix α(X) and a square matrix ß(X) such that if we choose $U(X)$ = α(X) + ß(X).V , so the looped system has a linear comportment, with a total decoupling of the inputs and the outputs [10].

From the matrix system:

$$\begin{cases} \dot{X} = A \cdot X + B(X) \cdot U \\ U = \alpha(X) + \beta(X) \cdot V \end{cases}.$$

Replacing U by its value we find:

$$\dot{X} = A \cdot X + B(X) \cdot \alpha(X) + B(X) \cdot \beta(X) \cdot V . \tag{3}$$

The matrix α(X) is chosen such that the term ($B(X)$·α(X)) compensates exactly the term ($A \cdot X$). Moreover, $B(X)$ is invertible, provided that:

$$I_L \neq 0 \quad \text{and} \quad E \neq 0 . \tag{4}$$

Consequently, we choose ß (X) $=B^{-1}(X)$. Let:

$$\dot{V}_{C_{11}} = v_{11}, \quad \dot{V}_{C_{21}} = v_{21}, \quad \dot{I}_L = v_{31}, \quad \dot{V}_{C_{12}} = v_{12}, \quad \dot{V}_{C_{22}} = v_{22}, \quad \dot{I}_L = v_{32} . \tag{5}$$

The matrixes α(X) and ß(X) are given as: $\alpha(X) = -B^{-1}(X) \cdot A \cdot X$, $\beta(X) = B^{-1}(X)$

Under the expressed conditions in (4), the values obtained for the decoupling calculation are given by (6)

$$A \cdot X = \begin{pmatrix} 0 & 0 & -b_0 X_{31} & 0 & 0 & -b_0 X_{32} \end{pmatrix}^{\mathrm{T}} , \tag{6}$$

$$B^{-1}(X)=\begin{pmatrix} \frac{X_{11}-E}{a_{11}EX_{31}} & \frac{X_{21}-E}{a_{21}EX_{31}} & \frac{1}{b_1E} & 0 & 0 & \frac{1}{b_1E} \\ \frac{X_{11}}{a_{11}EX_{31}} & \frac{X_{21}-E}{a_{21}EX_{31}} & \frac{1}{b_1E} & 0 & 0 & \frac{1}{b_1E} \\ \frac{X_{11}}{a_{11}EX_{31}} & \frac{X_{21}}{a_{21}EX_{31}} & \frac{1}{b_1E} & 0 & 0 & \frac{1}{b_1E} \\ 0 & 0 & \frac{1}{b_1E} & \frac{X_{12}-E}{a_{12}EX_{32}} & \frac{X_{22}-E}{a_{22}EX_{32}} & \frac{1}{b_1E} \\ 0 & 0 & \frac{1}{b_1E} & \frac{X_{12}}{a_{12}EX_{32}} & \frac{X_{22}-E}{a_{22}EX_{32}} & \frac{1}{b_1E} \\ 0 & 0 & \frac{1}{b_1E} & \frac{X_{12}}{a_{12}EX_{32}} & \frac{X_{22}}{a_{22}EX_{32}} & \frac{1}{b_1E} \end{pmatrix}, \quad (6)$$

with: $a_{11}=\frac{1}{C_{11}}, a_{21}=\frac{1}{C_{21}}, a_{12}=\frac{1}{C_{12}}, a_{22}=\frac{1}{C_{22}}, b_0=\frac{R_L}{L_L}, b_1=\frac{2}{L_L}$.

So, the feedback state can be expressed by (7):

$$\alpha(X)=\begin{pmatrix} \frac{b_0X_{31}}{b_1E} & \frac{b_0X_{31}}{b_1E} & \frac{b_0X_{31}}{b_1E} & \frac{b_0X_{32}}{b_1E} & \frac{b_0X_{32}}{b_1E} & \frac{b_0X_{32}}{b_1E} \end{pmatrix}^{\mathrm{T}}. \quad (7)$$

Once the feedback state is performed, the new inputs variables are contained in the vector $V = (v_{11}\ \ v_{21}\ \ v_{31}\ \ v_{12}\ \ v_{22}\ \ v_{32})^{\mathrm{T}}$, as indicated in Fig. 3.

Thus, in the case of a stacked multicellular converter, the nonlinear feedback allows to obtain $P\times 2$ linear relations completely decoupled between the new inputs variables and the $P\times 2$ state system variables.

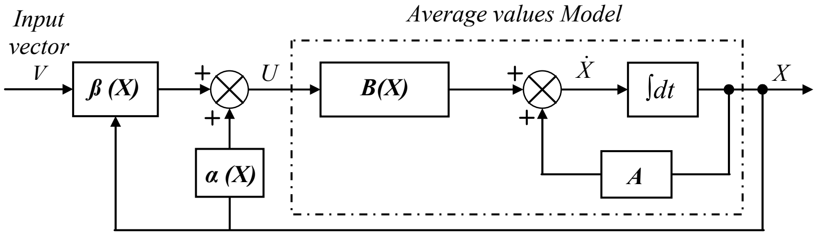


Fig. 3 – Decoupling with nonlinear feedback: functional representation.

It appears a singular points in the vicinity, where the nonlinear decoupling control loses its validity. These points are the zero crossing of the load current ($I_L = 0$) and the DC voltage ($E = 0$). Under these operating conditions, the system is not controllable [11]. In the case of a chopper, these singular points have no effect on this control, because they are outside the habitual operating range. On the other side, in the case of a SMC inverter, the load current becomes zero twice per fundamental period. It is then necessary to introduce a limitation of the measured current, in order to avoid the point ($I_L = 0$) as indicated in Fig. 4.

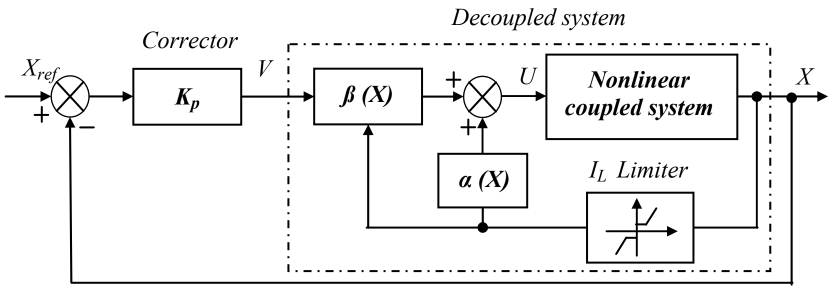


Fig. 4 − Enslavement of the decoupled system to a reference vector X_{ref}.

After decoupling between the different variables, we obtain $P\times2$ linear subsystems, each subsystem associates an input variable to a state variable ($\dot{X} = V$). It is now necessary to provide a second linear loop in order to set the dynamic on each state variable. This loop (Fig. 4), need as much feedback loops that there is state variable. Therefore the balancing of the floating voltages is obtained due the difference of the cyclic reports of two adjacent cells $u_{(i+1)1}$ and u_{i1} (α_{i1} and α_{i2} matrix U) which are calculated such that the output voltages V_{Ci1} and V_{Ci2} follow the reference voltages V_{Ci1ref} and V_{Ci2ref} with a minimum time (Fig. 4).

As presented in Fig. 4, we will consider a proportional corrector K_p which the control equation of the loop $i_1$or i_2 is given by (8):

$$v_{i1} = K_{pi1}\left(X_{i1ref} - X_{i1}\right), \tag{8}$$

with: $1 \leq i \leq P\times2$ and $K_{pi1} > 0$.

We obtain for each state variable a transfer function in open loop of the type [12] (s is the Laplace variable) :

$$T_{OL_{i1}}(s) = \frac{K_{pi1}}{s}. \tag{9}$$

The choice of the proportional constant is carried out by fixing a closed-loop dynamic for the system. The transfer function in closed loop is given by [13]:

$$T_{CL_{i1}}(s) = \frac{1}{1 + \left(s/K_{pi1}\right)}. \tag{10}$$

So we impose on each loop the desired dynamic. Under these conditions, we can with this type of regulator impose a given dynamic for each state variable [12].

4. **OBTAINED RESULTS**

We have made a numerical simulation of the system represented in Fig. 5, with MATLAB / SIMULINK. This is a 3×2 stacked multicellular converter, used as a chopper, supplying an *R-L* load, controlled by the decoupling control with nonlinear feedback. The parameters used in this simulation are given in Fig. 5.

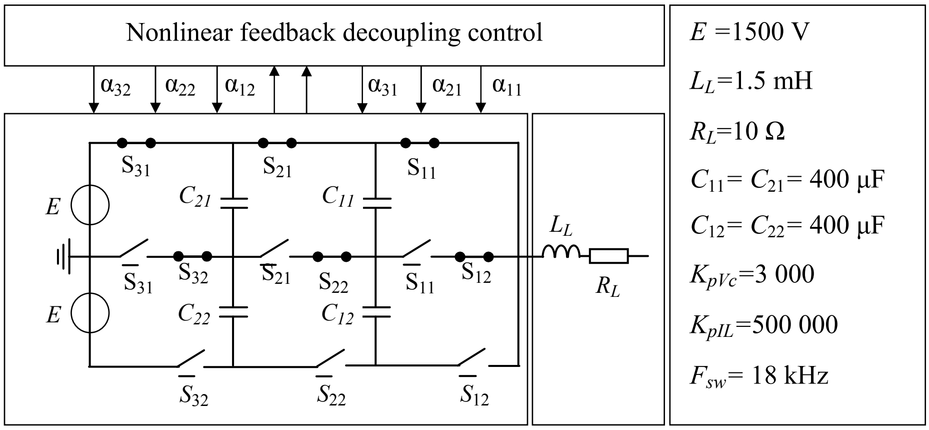
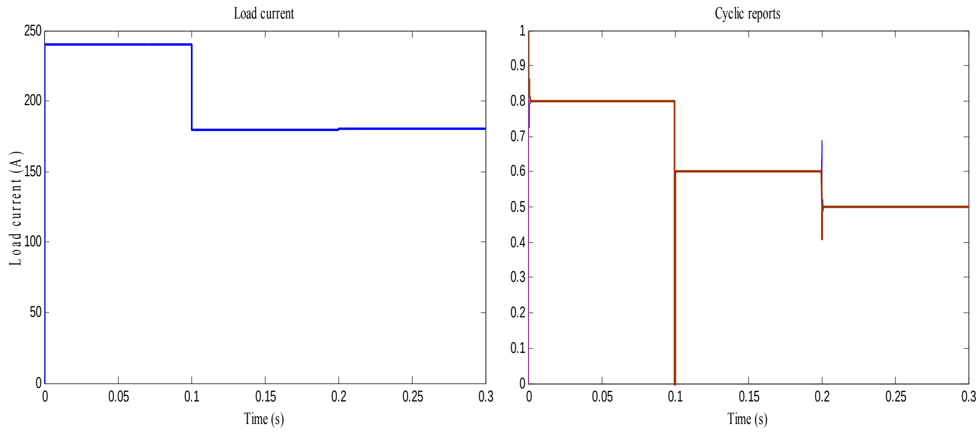


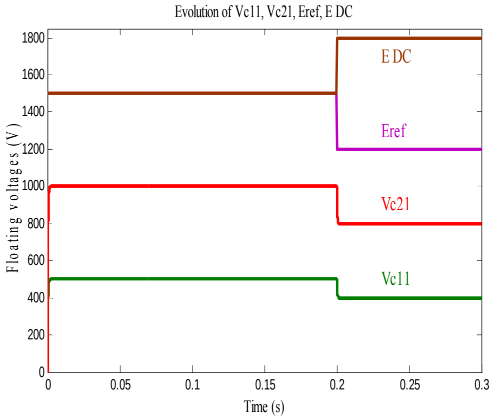
Fig. 5 − Studied system.

Fig. 6 and Fig. 7 represent the results obtained after simulation of the system represented in Fig. 5. The floating voltages are measured directly.

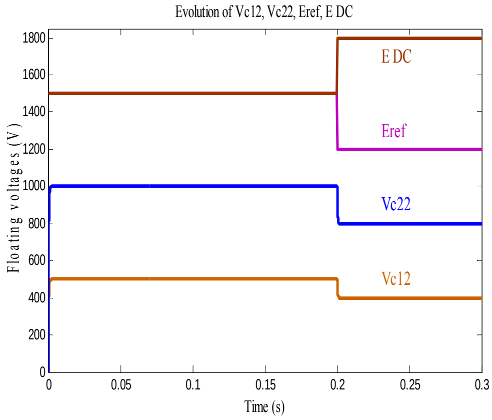


a) b)

Fig. 6 – Representation of: a) the load current; b) the cyclic reports.



Floating voltages of the stack 1 (a)



Floating voltages of the stack 2 (b)

Fig. 7 – Representation of the floating voltages of the stack 1 (a) and the stack 2 (b).

As we can see in Fig. 6a, when we decrease the current of 60 A at t = 0.1 s, the current follows very well this change, and this perturbation doesn't affect the voltages generated by the floating capacitors of the two stacks (Fig. 7(a,b)).

We perform two variations at t = 0.2 s (Fig. 7a,b). Firstly, we simulate a voltage drop of 300 V for the reference voltage E_{ref} . Secondly, we increase the converter supply voltage E_{DC} of 300 V. As results, the voltages generated by the floating capacitors follow the change of the reference voltage E_{ref} , on the other side, the variation of the converter supply voltage E_{DC} doesn't affect these voltages. Moreover, these two variations have no effect on the load current.

During the normal system operation the cyclic reports are at 0.8 (Fig. 6 b). Then, they decrease twice to compensate the two variations applied to the system and also to ensure the decoupling between the current and the voltage. The first variation for the current is at t = 0.1 s where they are at 0.6 and the second for the reference voltage E_{ref} is at t = 0.2 s where they at 0.5.

5. CONCLUSION

We can conclude from this work that, the SMC provides improvements in the field of the power electronics, because this topology ensure an equal distribution of the voltage constraints on the power components, it also allows to fractionate the input voltage into several fractions in order to reduce the switching of the power switches. But, with all this advantages this system is coupled; where we can't control the current and the voltage separately. For this reason we tried to decouple this system by controlling it with the decoupling control with nonlinear feedback.

This control has given very good results; where it assured a total decoupling between the inputs and the system outputs. Moreover, it assured a good regulation of the current and the floating voltages with a minimum response time. The multiplication of the switching frequency improves the performance of the system, and it ameliorates the output signals form.

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REFERENCES

1. K. Benmansour, A. Benalia, M. Djemai, J. Leon, *Hybrid control of a multicellular converter*, Elsevier, Nonlinear analysis: Hybrid systems, **1**, *1*, pp. 16–29, 2007.
2. L. Parvulescu, D. Floricau, M. Covrig, *Comparison between five-level flying capacitor structures*, Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **57**, *1*, pp. 40–51, 2012.
3. G. Gateau, T. A. Meynard, H. Foch, *Stacked Multicell Converter (SMC): Properties and design*, IEEE Power Electronics Specialists Conference, Vancouver-Canada, Vol. 3, 2001, pp. 1583–1588.
4. G. Gateau, T. A. Meynard, H. Foch, *Stacked Multicell Converter (SMC): Topology and control*, 9th European Conference on Power Electronics and Applications (EPE'2001), Graz-Austria, 2001, pp. 405–410.
5. A. M. Lienhardt, G. Gateau, T. A. Meynard, *Stacked Multicell Converter (SMC): Reconstruction of flying capacitor voltages*, IEEE Industrial Electronics Conference, 2005, pp. 691–696.
6. L. Delmas, G. Gateau, T.A. Meynard, H. Foch, *Stacked Multicell Converter (SMC): Control and natural balancing*, IEEE Power Electronics Specialists Conference (PESC'2002), Cairns-Australia, **2**, pp. 689–694, 2002.
7. J. Aguillon-Garcia, J.M. Fernandez-Nava, P. Banuelos- Sanchez, *Unbalanced Voltage Effects on a Single Phase Multilevel Inverter Due to Control Strategies*, 26th International Telecommunications Energy Conference (INTELEC'04), Chicago, 2004, pp. 140–145.
8. S. Hanafi, M.K. Fellah, A. Guebli, E. Chiali, *Commande du convertisseur multicellulaire série (7 cellules) par SVM avec régulation des tensions flottantes*, 2nd International Conference on Power Electronics and Electrical Drives (ICPEED'12), USTO-MB, Oran-Algeria, 2012.
9. A. Chouder, *Contribution à la commande des convertisseurs multicellulaires série*, Magister memory, Ferhat Abbas University of Setif, Algeria, 2010.
10. M. Aimé, *Evaluation et optimisation de la bonde passante des convertisseurs statiques: Application aux nouvelles structures multicellulaire*, Thesis, National Polytechnic Institute of Toulouse, France, 2003.
11. G. Gateau, *Contribution à la commande des convertisseurs multicellulaires série*, Thesis, National Polytechnic Institute of Toulouse, France, 1997.
12. G. Gateau, P. Maussion, T. A. Meynard, *De la modélisation à la commande non linéaire des convertisseurs multicellulaire série. Application à la fonction hacheur*, J. Phys III France **7**, *6*, pp. 1277-1305 , 1997.
13. G. Gateau, M. Fadel, R. Bensaid, T. A. Meynard, *Multicells converters: Active control and observation of Flying-Capacitor Voltages*, IEEE Transactions on Industrial Electronics, **49**, *5*, pp. 998–1008, 2002.