U.P.B. Sci. Bull., Series C, Vol. 74, Iss. 3, 2012 ISSN 1454-234x

A DIRECT CONTROL METHOD FOR MULTICELLULAR CONVERTERS

Bogdan Cristian FLOREA[1], Dan Alexandru STOICHESCU[2], Alexandru SPĂTARU[3]

În această lucrare este prezentată o metoda de control directă a convertoarelor multicelulare cc-cc serie. Aceste structuri au câştigat popularitate în perioada recentă datorită avantajelor oferite, şi anume: modularitate, reducerea constrângerilor pentru componente, eficienţă crescută. Pentru a evidenţia performanţele controlului propus, acesta va fi comparat cu un control de tip PWM. Rezultatele evidenţiază îmbunătăţirile aduse de metoda propusă faţă de una din metodele clasice de comandă a acestor topologii de convertoare.

In this paper, a direct control method for dc-dc series multicellular converters is introduced. Multicellular topologies have gained a lot of popularity because of their advantages over classical energy conversion structures. These advantages include: modularity, reduction of component constraints, high efficiency. In order to highlight the performance of the proposed method, it is compared to a PWM control. The results show the improvements of the proposed method compared to a classic control algorithm for these type of energy conversion topologies.

Keywords: multicellular converter, twisting, control, high order sliding mode

1. Introduction

Energy conversion has always presented interest for researchers, because of the many applications in which energy conversion systems are used. The efficiency of energy conversion has always been the main goal for the research. In high power applications in particular, the efficiency in the case of classical topologies is very low compared to the same topologies working in low power applications. The low efficiency is due to the high switching times of high power components.

The idea of multicellular converters (fig. 1) first appeared in the 1990s [1], and it proposed a series of elementary commutation cells, linked with floating

[1] PhD student., Faculty of Electronics, Telecommunications and Information Technology, University POLITEHNICA of Bucharest, Romania, e-mail: bogdan.florea@upb.ro

[2] Prof., Faculty of Electronics, Telecommunications and Information Technology, University POLITEHNICA of Bucharest, Romania, e-mail: stoich@elia.pub.ro

[3] Prof., Faculty of Electronics, Telecommunications and Information Technology, University POLITEHNICA of Bucharest, Romania

voltage sources. This allowed the distribution of high voltages over more switching elements and, as a consequence, the ability to use switching components with lower constraints and better performances.

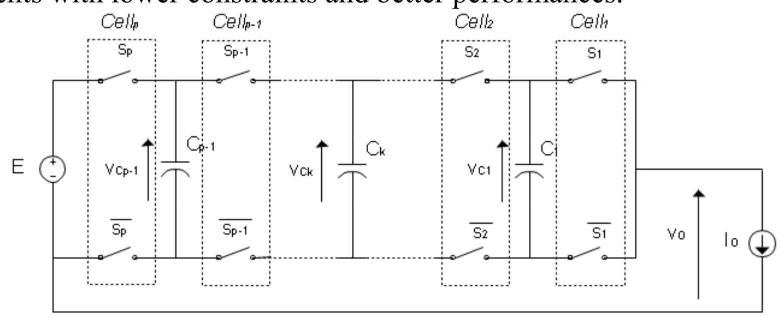

Fig. 1. Multicellular converter with *p* cells

The floating voltage sources that link the switching cells are actually floating capacitors. The voltage drop across them needs to be regulated by the control algorithm.

The complexity of the control is high because has to maintain the desired output voltage, while at the same time balance the capacitor voltages around the reference value.

Many control algorithms are proposed in literature, for example: a passivity based control [2], sliding mode control [3], PWM control [4].

The goal of this paper is to introduce an efficient control which improves the output error of the classical PWM control. The proposed control is based on a second order sliding mode algorithm which will be presented in section 3.

2. Multicellular converter model

The idea of the multicellular converter is that it distributes the high voltage over more switching elements. In order to avoid unbalanced usage of components, the voltage is distributed equally across each cell. That means that the voltage drop on each cell is equal to a fraction of the input voltage $\frac{E}{p}$, where p is the number of cells (fig. 1). In order to ensure that, we must determine the floating capacitor voltages:

$$V_{Cell_k} = V_{C_k} - V_{C_{k-1}} = \frac{E}{p}, k = 1 \dots p \tag{1}$$

where $V_{C_0} = 0, V_{C_p} = E$.

From equation (1), for $k = 1$, we have:

$$V_{Cell_1} = V_{C_1} - V_{C_0} = \frac{E}{p} \Rightarrow V_{C_1} = \frac{E}{p} \tag{2}$$

Increasing *k*, we find the general expression for the capacitor voltages:

$$V_{C_k} = \frac{kE}{p} \tag{3}$$

In order to determine the converter model, we consider two adjacent cells: $Cell_k$ and $Cell_{k+1}$ connected with the capacitor C_k (fig. 2).

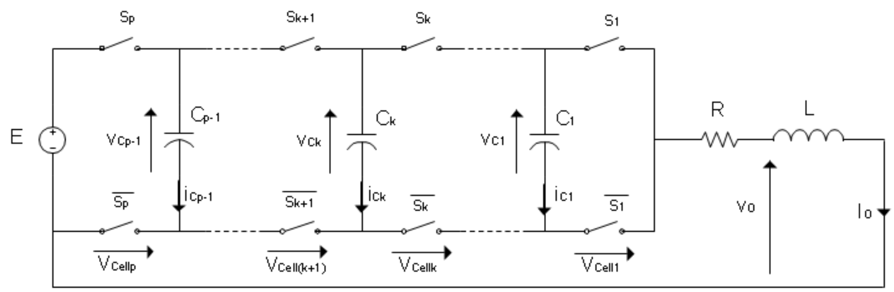

Fig. 2. Multicellular converter with *p* cells and an RL load

The capacitor voltage V_{C_k} is determined by the evolution of the capacitor current. This, in turn, is given by the configuration of the switches:

$$i_{C_k} = (s_{k+1} - s_k) i_O \tag{4}$$

where: $s_k = 1$ if the upper switch in cell k is conducting and $s_k = 0$ if the lower switch in cell k is conducting [5].

The capacitor voltage is then given by (5):

$$i_{C_k} = C_k \frac{dV_{C_k}}{dt} \Rightarrow \frac{dV_{C_k}}{dt} = \frac{(s_{k+1} - s_k)}{C_k} i_O \tag{5}$$

Equation (5) can be generalized for all capacitors. Next we determine the output voltage as the sum of all cell voltages (6):

$$V_O = \sum_{k=1}^{p} V_{Cell_k} = \sum_{k=1}^{p} (V_{C_k} - V_{C_{k-1}}) s_k \tag{6}$$

From equation (6), we note that we can have multiple voltage levels at the output, depending on the configuration of the switches. For a converter with *p* cells, we have *p+1* voltage levels: $0, \frac{E}{p}, \frac{2E}{p}, \ldots, \frac{(p-1)E}{p}, E$ [5]. This means that the voltage jumps at the output are smaller than the ones in classical structures.

For the multicellular converter with an RL load in fig. 2, the output current i_O is given by:

$$\frac{di_O}{dt} = \frac{V_O}{L} - \frac{R}{L} i_O \tag{7}$$

From equations (5), (6) and (7) we get the instantaneous model of the multicellular converter in fig. 2:

$$\begin{cases} \dot{V}_{C_1} = \dfrac{s_2 - s_1}{C_1} i_O \\ \dot{V}_{C_2} = \dfrac{s_3 - s_2}{C_2} i_O \\ \vdots \\ \dot{V}_{C_{p-1}} = \dfrac{s_p - s_{p-1}}{C_{p-1}} i_O \\ \dot{i}_O = \dfrac{(s_1 - s_2)}{L} V_{C_1} + \dfrac{(s_2 - s_3)}{L} V_{C_2} + \ldots + \dfrac{(s_{p-1} - s_p)}{L} V_{C_{p-1}} + \dfrac{s_p}{L} E - \dfrac{R}{L} i_O \end{cases} \tag{8}$$

For the remainder of this paper, we will use a 3 cell converter ($p = 3$) connected to an RL load.

3. Control method

The controller needs to accomplish two tasks: provide the required output voltage and balance the capacitor voltages around the reference values.

Many types of controllers exist in literature. One very popular type of control is the sliding mode control. It has been around for a very long time and it has been thoroughly researched. The disadvantage of using this type of control is the existence of chattering: high frequency oscillations around the sliding surface. Some solutions have been proposed, like replacing the sign function of the sliding mode with a smoother function in the vicinity of the origin. However, this solution leads to the loss of accuracy and robustness of the system [6].

Another solution is to use higher order sliding modes. They act on the controlled value, as well as on its high order time derivatives. This way, the chattering is reduced significantly and the robustness is preserved.

An r^{th} order sliding mode is determined by:

$$s = \dot{s} = \ddot{s} = \ldots = s^{r-1} = 0 \tag{9}$$

where s is the sliding surface.

The proposed control method is based on the twisting algorithm, which is a second order sliding mode.

The phase trajectory of the twisting algorithm is shown in figure 3.

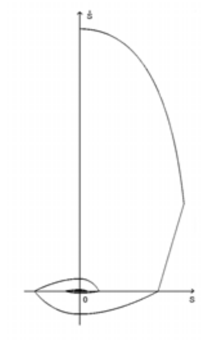

Fig. 3. Phase trajectory of the twisting algorithm

The control law for the algorithm is given by:

$$\dot{u}(t) = \begin{cases} -u, |u| > 1 \\ -V_m sign(s), s\dot{s} \leq 0, |u| \leq 1 \\ -V_M sign(s), s\dot{s} > 0, |u| \leq 1 \end{cases} \tag{10}$$

where: $V_M > V_m, V_m > \dfrac{4\Gamma_M}{s_0}, V_m > \dfrac{\phi}{\Gamma_m}, \Gamma_m V_M - \phi > \Gamma_M V_m + \phi$.

The twisting algorithm is responsible for choosing the required output voltage in order to drive the system along the phase trajectory.

The second part of the control is to choose to correct switching combination, so that the required voltage is ensured and the floating capacitor voltages are regulated.

In order to determine what the next switching combination is, we must analyze the effect of combination on the capacitor voltages and on the output. There are $2^p = 2^3 = 8$ operating modes. The operating modes of the 3 cells converter are presented in table 1.

Table 1

Operating modes of the multicellular converter

s_1	s_2	s_3	V_{C1}		V_{C2}		V_O
			$i_O \geq 0$	$i_O < 0$	$i_O \geq 0$	$i_O < 0$	
0	0	0	-	-	-	-	0
0	0	1	-	-	V_{C2}+	V_{C2}-	E/3
0	1	0	V_{C1}+	V_{C1}-	V_{C2}-	V_{C2}+	E/3
0	1	1	V_{C1}+	V_{C1}-	-	-	2E/3
1	0	0	V_{C1}-	V_{C1}+	-	-	E/3
1	0	1	V_{C1}-	V_{C1}+	V_{C2}+	V_{C2}-	2E/3
1	1	0	-	-	V_{C2}-	V_{C2}+	2E/3
1	1	1	-	-	-	-	E

We can see that for all voltage levels different from *0* or *E*, we have redundancy. Also, for those voltage levels, the capacitor voltages are changed. This redundancy allows us to choose the best combination so that we can have the output voltage required and, at the same time, balance the floating capacitor voltages.

Another consequence of having redundancy is that we can optimize the control in order to prolong the life of the switching elements. This is achieved by prioritizing the capacitor voltages that need to be balanced and choosing a combination which requires a minimum number of commutations from the current operating mode.

In order to do this, we must first compute all possible future modes F_M of operation from the current state s_c for the required output voltage:

$$F_M = \begin{bmatrix} s_{1_1} & s_{2_1} & \cdots & s_{p_1} \\ s_{1_2} & s_{2_2} & \cdots & s_{p_2} \\ \cdots & \cdots & \cdots & \cdots \\ s_{1_i} & s_{2_i} & \cdots & s_{p_i} \end{bmatrix} \quad (11)$$

$$s_c = \begin{bmatrix} s_1 & s_2 & \ldots & s_p \end{bmatrix}$$

The next step is to determine the number of commutations N_S from the current state s_c to all the possible future states:

$$N_S = \begin{bmatrix} m_1 & m_2 & \ldots & m_i \end{bmatrix}$$

$$m_k = \sum_{j=1}^{p} \left| u_c(j) - F_M(k,j) \right|, k = 1 \ldots i \quad (12)$$

The combination with the minimum number of switches m_k is chosen.

4. Results

The proposed controller was tested in MATLAB/Simulink simulation with the following conditions:

$E = 300V,\ C_1 = C_2 = 33\mu F,\ L = 0.5mH,\ R = 10\Omega,\ f = 10kHz$

In order to test the performance of the control, it was compared with a PWM control. The PWM control for multicellular choppers has the advantage of ensuring a natural balance of the capacitor voltages [7], but the steady state error is considerably higher than the proposed control method.

In figures 4 and 5 we see the output current for the 2 control methods. The reference is 2.5A for both cases. We clearly see that the oscillations for the PWM method is higher than for the direct control proposed in this paper. Also, the overshot at start-up in the case of PWM control is very high and potentially dangerous for the load.

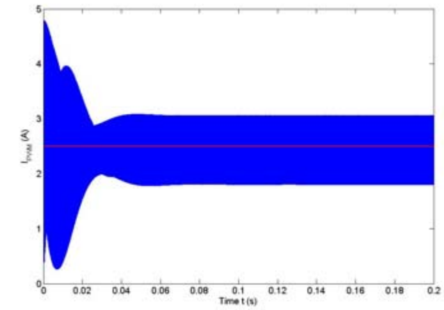

Fig. 4. Output current for PWM control

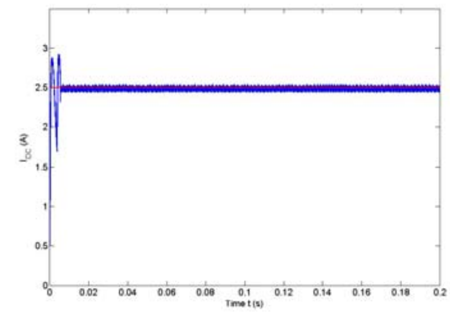

Fig. 5. Output current for direct control

The capacitor voltages are balanced in both cases (figures 6, 7, 8 and 9), but again, in the case of PWM control, the initial overshot is significant, and it is the cause for the current overshot. In the proposed direct control, the overshot is close to zero and the capacitor voltages are maintained balanced.

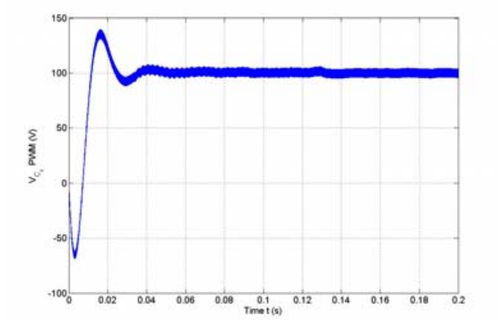

Fig. 6. V_{C1} for PWM control

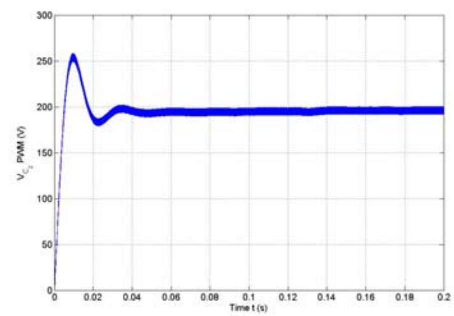

Fig. 7. V_{C2} for PWM control

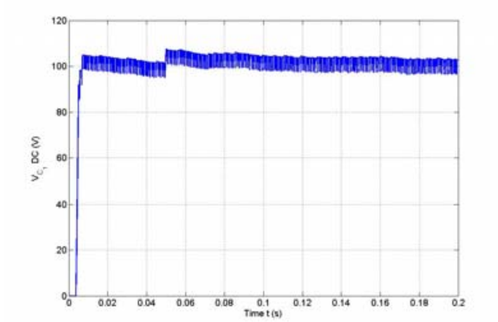

Fig. 8. V_{C1} for direct control

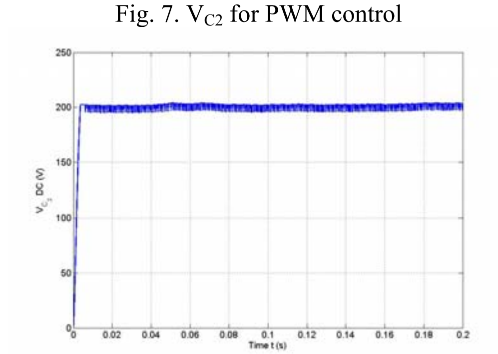

Fig. 9. V_{C2} for direct control

A comparison between the two methods is presented in table 2.

Table 2

Comparison between the proposed method and PWM control

	PWM control	Direct control
ΔV_{C1max} (V_{C1ref} = 100V)	42.6V	9.3V
ΔV_{C2max} (V_{C2ref} = 200V)	57.2V	10.7V
t_{tran}	32ms	12ms

As it is shown in table 2, the maximum deviation for the capacitor voltages in the case of PWM control is very high, especially during the transient time (figures 6 and 7). This can be dangerous for the circuit and the load and additional circuits are needed in order to have a safe operation. The proposed method has a much lower maximum variation of capacitor voltages, even during transient time, variation which is contained in the ±10% interval which we allowed for the floating voltages. One can also see the reduction of transient time for the proposed method, which provides a better response for the circuit.

5. Conclusions

The proposed method works with good results, which was highlighted in comparison with the classic PWM control. The results show that for the same configuration, the results are improved about 10 times, and at the same time, the dangerous overshot is eliminated. In order to protect the load in the case of PWM control, a start-up routine is necessary, whereas in the case of the proposed direct control, this step is eliminated, thus making the system more responsive. This is shown also in terms of the transient time for the system, which is greatly improved in the proposed method.

R E F E R E N C E S

[1] *Th. Meynard, H. Foch,* "Dispositif de conversion d'energie electrique a semiconducteur", brevet francais no. 91,09582, Europe, Japan, USA, Canada, 92,00652

[2] *H. Sira-Ramirez, R.P. Moreno, R. Ortega, M.G. Esteban* "Passivity-based controllers for the stabilization of dc-t-dc power converters", Automatica, 33, pag. 499-513, 1997

[3] *L.Amet, M. Ghanes, J.P. Barbot,* "Direct control based on sliding mode techniques for multicell serial chopper", American Control Conference 2011, pag. 751-756, 2011

[4] *G. Gateau, M. Fadel, P. Maussion, R. Bensaid, T.A. Meynard,* "Multicell converters: active control and observation of flying-capacitor voltages", IEEE Transactions on Industrial Electronics, Volume 49, Issue 5, pag. 998-1008, 2001

[5] *K. Benmansour, J. Deleon, M. Djemai,* "Adaptive observer for multi-cell chopper", Second International Symposium on Communications, Control and Signal Processing ISCCSP, Marakesh, Morocco, 2006

[6] *W.Perruquetti, J.P. Barbot,* "Sliding mode control in engineering", CRC Press, 2002

[7] *T. Meynard, M. Fadel, N. Aouda,* "Modeling of multilevel converters", IEEE Trans. Ind. Electron., vol. 44, pp. 356364, June 1997.