Decentralized Controller for a Multilevel Flying Cap Converter

This awarded paper for Young Engineers presents a decentralized method to balance the capacitor voltages of a Flying-Cap converter. In this study, a change of variable is proposed replacing the voltage of the capacitors by the cell-voltages to provide an appropriate model of the converter. The control strategy involves several cell-voltage-balancing local controllers associated to each cell and a global output current controller. The local controllers cancel the difference between their own local cell-voltage with the average value of the neighboring cell-voltages. Using this control method any number of cells constituting the converter can be handled. It provides also an auto-balancing property in case of an insertion or a removal of an active cell during operation, which can be useful to address fault-tolerant concerns. Furthermore, the study demonstrates that the dynamics of the two types of loops, the cell-voltage balancing and the output current regulation are uncorrelated. **Miguel Vivert, Marc Cousineau, Philippe Ladoux, Pontificia Universidad Javeriana, Bogotá, Colombia; Joseph Fabre, LAPLACE, Université de Toulouse, CNRS; Toulouse, France**

Multicellular converters are widely used in medium and high-power applications. Ones of the most popular multilevel topologies are the FC-converters and the multiphase converters. One of the main challenges for the control of multilevel converters is to regulate a large number of internal state variables. One solution is to decentralize the control. The technique consists to split the main controller into several local controllers, each managing only one part of the system. To balance the inductor currents, each leg current is compared with the neighbouring leg currents and the difference is cancelled by a corrector. Using a similar approach, the interleaving of the carrier signals of each leg is obtained. An adaptation of this method for the control of a FC-converter is proposed here.

Description of the system

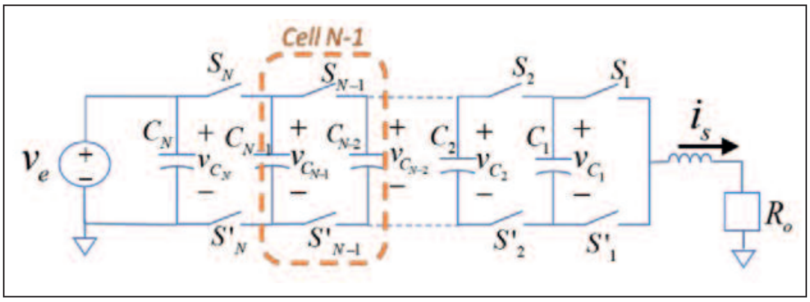
The system is a flying-cap converter made of N cells. Figure 1 shows the topology of theconverter.

Defining the CV variable as $v_j = v_{cj} - v_{cj-1}$, equation 1 shows the obtained model.

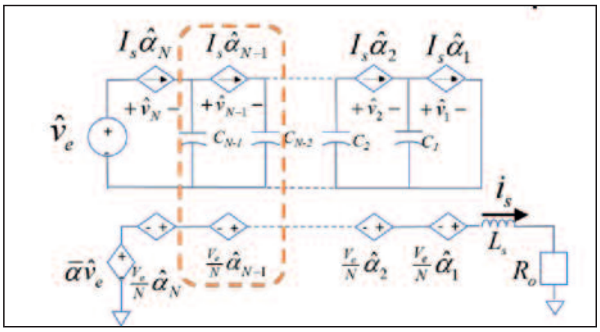
Equation 1

$$\begin{cases} \dot{V} = \frac{1}{C} i_s A_{sys} \alpha + E \dot{v}_e \\ \dot{i}_s = \frac{1}{L_s}\left(\alpha^T V - i_s R_o\right) \end{cases} \quad (1).$$

where A_{sys} and E are the matrices related to the topology of the converter, V and α are the vectors respectively of the cell-voltages and the cell's duty-cycles.



ABOVE Figure 1: **Schematic of the FC-converter where the cells are cascaded (connected in series)**



RIGHT Figure 2: **Small-signal model of the FC-converter**

In order to perform a small-signal analysis, the system has to be linearized. Equation 2 shows the system linearized.

Figure 2 shows the resulting small-signal model of the converter. This figure clearly shows that the current and the CVs are decoupled.

Design of the controllers

Figure 3 shows the block diagram of the proposed method of control with the bypass selector.

The LC receives the capacitor voltages of its own cell v_{cj}, computes its local CV v_j, and receives also the CVs of the neighbouring cells v_{j-1} and v_{j+1}. The error between v_j and the average value of v_{j+1} and v_{j-1} is computed and cancelled with $K_{v(s)}$. Then, this compensation is added to the output of the OCC to provide the local duty-cycle α_j. If a failure occurs on the cell, the cell is disabled ($en_j = 0$) and the local signals exchanged between the adjacent LCs are bypassed in order to maintain the communicating chain closed. Inserting a cell consists to enable the cell ($en_j = 1$) and reactivates the communications with the neighbouring LCs.

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Equation 2

$$\begin{cases}\dot{\hat{\mathrm{V}}} = \frac{1}{C} I_s \mathrm{A}_{\mathrm{sys}} \hat{\alpha} + \mathrm{E}\dot{\hat{v}}_e \\ \dot{\hat{i}}_s = \frac{1}{L_s}\left(\bar{\alpha}\hat{v}_e + \frac{\bar{v}_e}{N}\mathrm{V}_1^{\mathrm{T}}\hat{\alpha} - R_o \hat{i}_s\right)\end{cases} ; \quad \text{with} \quad \begin{matrix}\alpha = \bar{\alpha}\mathrm{V}_1 + \hat{\alpha} \\ \mathrm{V} = \frac{\bar{v}_e}{N}\mathrm{V}_1 + \hat{\mathrm{V}}\end{matrix} ; \begin{matrix} i_s = I_s + \hat{i}_s \\ v_e = \bar{v}_e + \hat{v}_e\end{matrix} \quad \text{where } \mathrm{V}_1 = \begin{bmatrix}1 \\ \vdots \\ 1\end{bmatrix} \tag{2}$$

Where $\hat{\alpha}, \hat{\mathrm{V}}, \hat{i}_s, \hat{v}_e$ are the small-signal variables.

Equation 3

$$\begin{cases}\hat{\mathrm{V}} = \frac{I_s}{Cs} K_v(s) \mathrm{A}_{\mathrm{sys}} \mathrm{D}_{\mathrm{iff}} \hat{\mathrm{V}}' + \mathrm{E}\hat{v}_e \\ \hat{i}_s = \frac{1}{L_s s + R_o}\left(\bar{\alpha}\hat{v}_e + \bar{v}_e K_s(s)\left(\hat{I}_{ref} - \hat{i}'_s\right)\right)\end{cases} \tag{3}$$

control method is that both control loops are completely uncoupled, i.e. the cell-voltage is not affected by the current controller and vice versa, as shown by (3).

In equation 3) the variables are not linked together. The gains of the controllers are selected to have a bandwidth 60 times less than the switching frequency for the cell-voltage balancing controller and 50 times less for the current controller.

Simulation and experimental results

The simulation results are obtained for a 5-cells FC-converter with $v_e = 450$ V, $C_1 = C_2 = C_3 = 42$ µF, $C_4 = C_5 = 21$ µF, $L_s = 200$ µH, $R_o = 18.75$ Ω and a switching frequency $f_{sw} = 10$ kHz.

The first test concerns the current loop response to a load transient on Ro stepping from 18.75 Ω to 12.5 Ω. The second test is related to the insertion of the cell 3 (Figures 4 and 5).

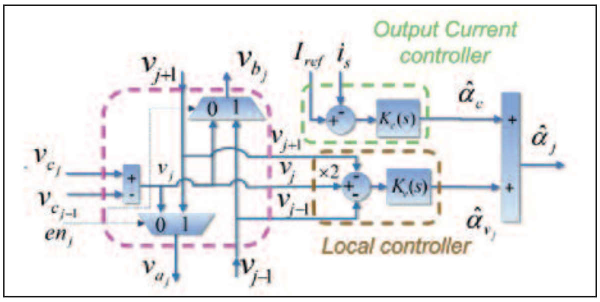

Figure 3: **Block diagram of the control loops**

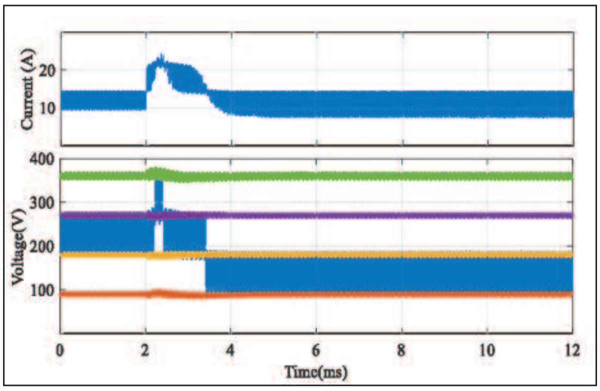

Figure 4: **Response to a load transient**

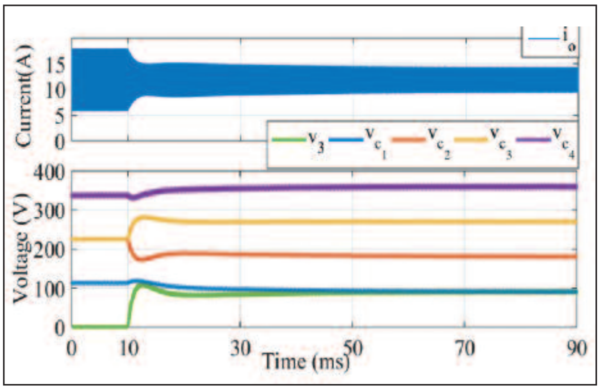

Figure 5: **Inserting of cell 3 during operation**

The experimental results are the same tests of the simulation and are done with the same parameters, increasing 50% the load transient and for the dynamic insertion of cell 3 during operation.

Figure 6 shows the load transient response of the system with a settling time of 5 ms for the current. The CV are lightly disturbed by the step event. Figure 7 shows the voltages of the capacitors and the cell-voltage v_3 during the insertion of cell 3. The CVs are well balanced stepping from $v_e/4$ to $v_e/5$ with a settling time of 40 ms. The current is almost not affected by the insertion, validating the uncoupling of the system.

Summary

This paper presents a decentralized control strategy dedicated to the cell-voltages balancing in a flying-cap converter. Using local communications with their neighbors, the local controllers are able to balance their own cell-voltage with the others for any number of cells N involved in the converter, without having access to neither the value of N nor the value of the input voltage.

A theoretical study is developed providing both a model of the converter

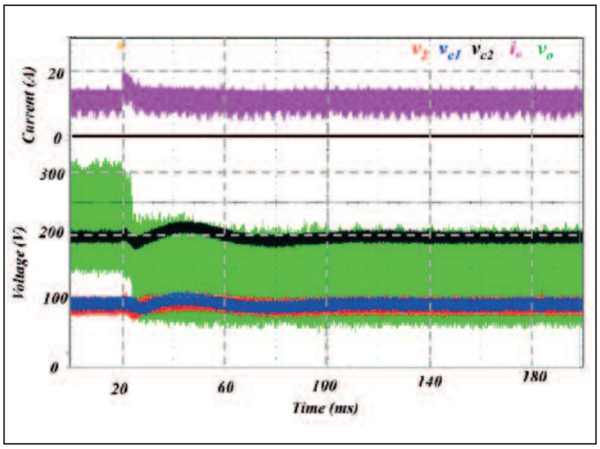

Figure 6: **Load transient response of the FC-converter**

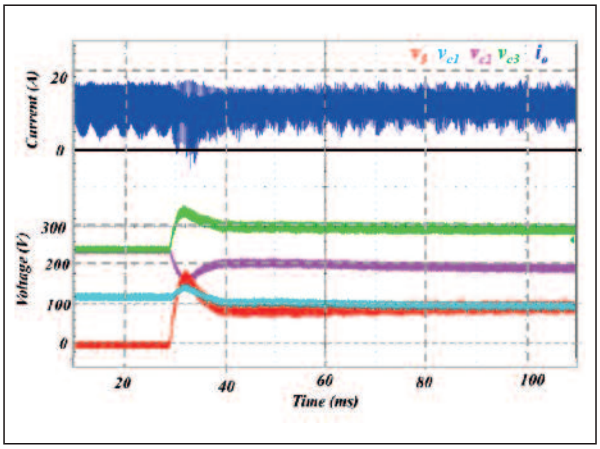

Figure 7: **Output current - insertion of the cell 3 during operation (Math $v_3 = v_{c3} - v_{c2}$)**

using the cell-voltages as the new state variables and an analytical description of the overall system involving the two types of control loops, i.e. the CV balancing and the output current regulation. It is then shown that the two loops are uncorrelated. Moreover, this control strategy allows to easily insert or remove an active cell of the converter by using a simple bypass circuit included in each local controller, the balancing functionality remaining always operational.

The simulations of the converter responses to several types of transients and the experimental results obtained thanks to a prototype implemented in the laboratory validate the expected performances of the proposed control method and confirm it relevance.

Literature

"Decentralized controller for the cell-voltage balancing of a Multilevel Flying Cap Converter", Miguel Vivert, Young Engineer Awardee PCIM Europe 2019, Pontificia Universidad Javeriana, Bogotá, Colombia; PCIM Europe 2019 Proceedings, pages 571 - 578

PCIM Europe 2019 Proceedings, pages 344 - 351