A GENERIC PASSIVITY BASED CONTROL FOR MULTICELLULAR SERIAL CONVERTERS

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Abstract : Multicellular converters appeared for a few years in order to palliate some drawbacks of the classical structures. Such structures allow to reduce the voltage throughout the switches and the number of discrete values of the voltage in the load is directly related to the number of commutation cells. In opposing view, the control of a multicellular converter is more complex. In this paper a generic controller for a multicellular serial converter is developed, based on a generalization of Passivity Based Control (PBC) fitted to bond graph formalism. The generic state equations are deduced from the original bond graph model using the notion of commutation cells. The whole approach is presented in a formal way and the performances of the controller realised will be tested on an example.

Keywords : Passivity Based Control, Non-linear Control, Multicellular Converter, Commutation Cell, Bond Graph, Power Converter.

1. INTRODUCTION

Applications in power systems frequently use DC-DC converters. Usually, basic architectures like boost, buck or Cuk converters are elaborated. Nevertheless, for several years, a new class of DC-DC converters, called multicellular converters, appeared in order to palliate some drawbacks of the basic structures recalled above (Chiasson, *et al.,* 2003), (Schibli, *et al.,* 1998). DC-DC multicellular converters allow to reduce the voltage throughout the switches (in general IGBT or MOSFET transistors) and the number of discrete values of the voltage in the load being directly related to the number of commutation cells, a better approximation of the desired wave form can be obtained. In opposing view, the control of such a converter is more complex. The paper focuses on the multicellular serial converter, the aim being to determine a control strategy independently of the number of cells.

The approach uses bond graph formalism and the notion of commutation cell in to determine a generic state equation. Then a control strategy based on passivity is elaborated.

The paper is organized as follows. Section 2 provides some recalls about bond graph modelling of the continuous part of switching systems with ideal switches and the important notion of commutation cells. In section 3, the principles of PBC theory fitted to bond graph formalism are exposed and the different stages leading to the controller recalled (Ortega, 1998), (Ortega, *et al.*, 2002). Section 4, is devoted to determine the generic state equation of the multicellular serial converter and its associated controller synthesized with PBC method. Finally, an example is presented illustrating the previous results.

2. BOND GRAPH MODELLING AND PASSIVITY BASED CONTROL

2.1. Bond graph formalism

Created by H.M. Paynter, the bond graph formalism allows to model continuous systems and by extension, the continuous part of hybrid dynamical systems. Based on the transfer of energy which is figured by bonds and using the analogies between the various fields of the physic, this formalism models, with a unique approach, engineering components of is , electricity, hydraulics,….(Karnopp, *et al.*, 1990). Consequently, any physical system with switching components can be modelled by the generic bond graph of figure 1.

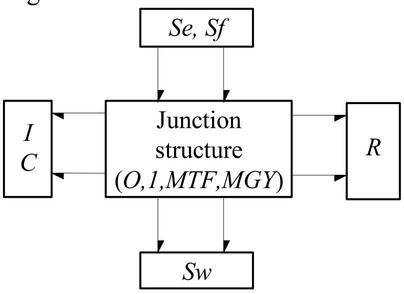

Fig. 1. Structure of a general bond graph

Beside the standard fields for sources, storage and dissipative elements, it includes a particular field for ideal switches (Sw). These extra elements either behave like flow or effort sources according to their state (Cormerais, 1998). The topology of the system is represented by the junction structure depicted on figure 1.
For any acceptable mode (or configuration of the switches), causality can be assigned so as to maximise the number of storage elements in integral causality and define a solvable input-output pattern. Figure 2 represents the block diagram deduced from the causal bond graph in a mode where no derivative causality is present.
In the following, for the sake of simplicity (even if it is not necessary for the proposed approach to work), it will be assumed that whatever the mode, no derivative causality is present in the system.

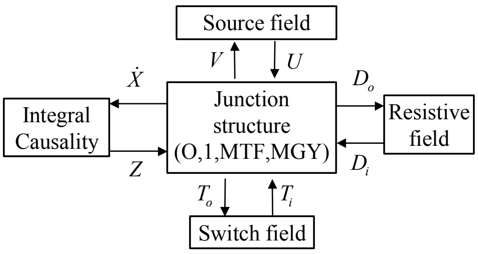

Fig. 2. block diagram deduced from the bond graph in one mode

The state vector X gathers the energy variables associated with the storage elements. T_i is made of the power variables imposed by the switches in the chosen mode; T_o is its conjugate. The outputs of the junction structure can be related to its inputs using a so-called standard implicit form (Buisson, *et al.,* 2002) :

$$\begin{pmatrix} \mathbf{I} \\ 0 \\ 0 \end{pmatrix} \dot{X} = \begin{pmatrix} S_{11} & S_{13} & 0 & S_{14} & 0 & S_{15} \\ -S_{13}^T & S_{33} & -\mathbf{I} & S_{34} & 0 & S_{35} \\ -S_{14}^T & -S_{34}^T & 0 & S_{44} & -\mathbf{I} & S_{45} \end{pmatrix} \begin{pmatrix} Z \\ D_i \\ D_o \\ T_i \\ T_o \\ U \end{pmatrix} \qquad (1)$$

Relation (1) is deduced from one particular mode, characterized by $T_i = 0$, but it remains formally true in any other mode. The S_{ii} matrices are skew symmetric.

2.2 The notion of commutation cell

In the case where switching commutate by pairs, the notion of commutation cell can be used allowing the determination of a new causal bond graph, topologically simpler and with fixed causality in any available mode (Buisson, *et al.,* 2001).
The principle of the method is first to determine the commutations cells, then, for each of them, to determine the generic input/output relation in any available mode.
The Boolean control inputs of the switches in the original model become variable parameters in the input/output relations of the commutation cells.
The main advantage of such a transformation is that it leads to a unique generic expression of the implicit standard form (cf. relation (2)) which depends on the Boolean inputs as formal parameters. Indeed, matrices S_{ij} possibly depend on the control Booleans, the latter being denoted by vector □ in the following.

$$\begin{pmatrix} \mathbf{I} \\ 0 \end{pmatrix} \dot{X} = \begin{pmatrix} S_{11} & S_{13} & 0 & S_{15} \\ -S_{13}^T & S_{33} & -\mathbf{I} & S_{35} \end{pmatrix} \begin{pmatrix} Z \\ D_i \\ D_o \\ U \end{pmatrix} \qquad (2)$$

The generic state equation can be easily deduced from (2) by introducing the constitutive relations on the resistive and storage elements.

$$D_i = LD_o \qquad Z = F\,X$$
$$H = L\left(I - S_{33}L\right)^{-1} \qquad (3)$$

where *L*, *F* are symmetric definite positive, and *H* definite positive
We have the following expression for the state equation :

$$\dot{X} = \left[S_{11} - S_{13}HS_{13}^T\right]F\,X + \left[S_{15} + S_{13}HS_{35}\right]U \qquad (4)$$

with *H* a definite positive matrix such that :

$$H = L\left(I - S_{33}L\right)^{-1} \qquad (5)$$

Let consider an output *Y* of the system made of linear combinations of the junction structure output variables. We have :

$$Y = CX_i + D\dot{X}_d + MU \qquad (6)$$

Furthermore, if the state variables are continuous at commutation time, the equivalent average model can be directly determined.

Definition of an elementary commutation cell : Considering the available modes for the system, an elementary commutation cell is a set of causal paths of type 1, connex in their set (A causal path 1 is a switching causal path i.e. a causal path between two switches whose causality changes at least one time considering all the available modes and two causal paths are connex if and only if they have at least one common bond).

The input/output bonds of the commutation cell are the bonds which are adjacent to the junctions of the commutation cell but do not belong to it. Their causality does not depend upon the mode. The effort/flow variables associated to these bonds define the input and output vectors S_{in} and S_{out} of the commutation cell, as depicted in Figure.2. The Switches block corresponds to the switches belonging to the switching causal paths of the commutation cell (Buisson, *et al.,* 2001).

3. A BOND GRAPH BASED FORMULATION OF PASSIVITY BASED CONTROL

PBC is known as an efficient continuous technique for the regulation of switching physical systems that requires the knowledge of an average model. The state equations deduced from bond graph models leading easily to a Port Controlled Hamiltonian (PCH) formulation that is this form which has been adopted in the following. Under this assumption, equations (4) and (5), which fundamentally define a state representation for the exact switching system whose control variables are Boolean, can also be interpreted as its average model provided that the same variables are considered as continuous in the set [0,1].
The matrix representation for the state average model of a switching system in standard PCH formulation has the following expression (Ortega *et al.*, 2002):

$$\dot{X} = \left[J(\rho) - R_a(\rho)\right]\frac{\partial H_t(X,\rho)}{\partial X} + G(\rho)U \qquad (7)$$

X the state vector of the average model
ρ the control variable
J the skew-symmetric interconnection matrix
R_a the symmetric dissipation matrix
H_t the energy stored in the system
G the power input matrix
H_t and matrices J, R, G potentially depend on the control variable ρ.

Since S_{11} is a skew symmetric matrix, it can be considered as an interconnection term from a PCH point of view. In return, H, and consequently $S_{13}HS_{13}^T$, are not symmetric in the general case (except when $S_{33} = 0$). Therefore it is necessary to separate the latter term into two parts, namely a skew symmetric one H_a, and a symmetric one H_s, in order to identify them respectively with an interconnection term and with a dissipation one. Then, the state equation can be written as (Morvan, *et al.*, 2004):

$$\dot{X} = \left[\left(S_{11} - S_{13}H_aS_{13}^T\right) - S_{13}H_sS_{13}^T\right]FX + BU \qquad (8)$$

Identifying (11) and (13), we get:

$$J(\rho) = S_{11} - S_{13}H_aS_{13}^T \qquad R_a(\rho) = S_{13}H_sS_{13}^T$$
$$\frac{\partial H_t}{\partial X} = F\,X \qquad G(\rho) = B \qquad (9)$$

The stage of the control synthesis :
- Starting from this PCH formulation of the model, the control objective will be to make the observation variable defined by (6) follow a prescribed reference:

$$Y = Y_c \qquad (10)$$

- Let $\tilde{X}$ be the error vector with

$$\tilde{X} = X - X_c \qquad (11)$$

- Using this error vector instead of the original state vector, the average model can be rewritten as:

$$\dot{\tilde{X}} - (J - R_a)F\,\tilde{X} = GU - \left[\dot{X}_c - (J - R_a)F\,X_c\right] \qquad (12)$$

- In PBC method a damping injection is performed by adding some dissipation on the error vector, by means of a matrix denoted by R_1 ($R_1 > 0$). Thus equation (12) becomes:

$$\dot{\tilde{X}} - \left(J - (R_a + R_1)\right)F\,\tilde{X} = GU - \left[\dot{X}_c - (J - R_a)F\,X_c - R_1F\,\tilde{X}\right] \qquad (13)$$

Then, the right hand side of this first order ordinary differential equation has to be null in order to ensure an asymptotic cancellation of the error.
- Finally, the PBC strategy leads to the following system :

$$\dot{X}_c - \left[J(\rho) - R_a(\rho)\right]F\,X_c - R_1F\left(X - X_c\right) = BU \qquad (14)$$
$$Y = Y_c \qquad (15)$$

These two equations define the controller dynamics under an implicit form (the variables are the control ρ and X_c). Knowing that X_c is a function of the control variable, this system can be explained as an explicit differential equation system in terms of ρ.

4.THE GENERIC STATE EQUATIONS OF THE MULTICELLULAR SERIAL CONVERTER

4.1 Introduction

Let consider the generic electric scheme of the multilevel serial converter that can be used for the control of DC-motors. From an electrotechnical point of view this converter is constituted of three type of cells such as depicted on the figure 3 : one source cell, *k* elementary cells, one load cell. Since, in normal conditions, the switches commutate by pairs (T1 with T2, T1,i with T2,i and so on) the notion of commutation cell can be used to determine an equivalent bond graph model of the system in which switches are not modeled by sources any longer, but rather by modulated transformers and/or gyrators. The Boolean control inputs of the original model become the coefficients of those new elements.

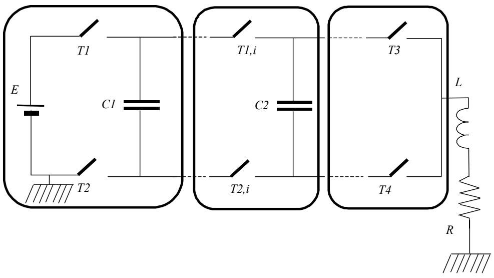

Fig. 3. The serial multilevel converter

The objective is to control the voltage in the capacitor and the current in the load.

4.2 The determination of the generic state equation using commutation cells

Considering the available modes for the system, an elementary commutation cell is a set of switching causal paths (a switching causal path is a causal path between two switches whose causality changes at least one time considering all the available modes) connex in their set. Two causal paths are connex if and only if they have at least one common bond.

The input/output bonds of the commutation cell are the bonds which are adjacent to the junctions of the commutation cell but do not belong to it. Their causality does not depend upon the mode. The effort/flow variables associated to these bonds define the input and output vectors S_{in} and S_{out} of the commutation cell.

One time the commutation cells determined, a general input/output relation can be determined for each of them depending of a Boolean parameter. A causal bond graph for the multicellular serial converter is represented on the figure below. It that mode the even switches are closed and the odd switches are opened. The commutation cells being isolated, it is easy to determine the generic input/output relations available whatever the state of the switching of the corresponding commutation cell. Finally, the following expressions are obtained (the components (effort/flow) of input/output vectors corresponding to the commutation cells are deduced from the causal bond graph of figure 4):

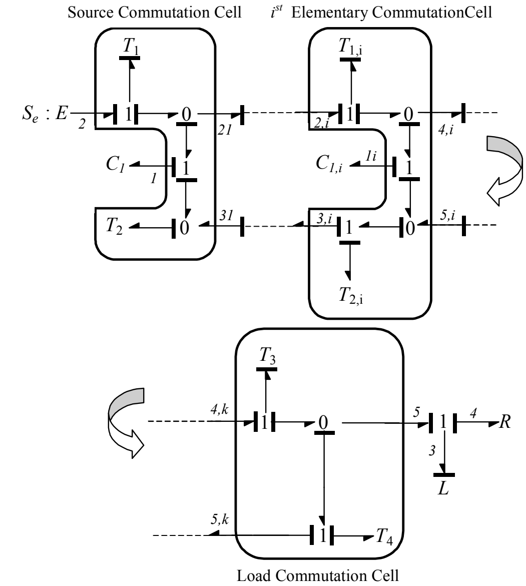

Fig. 4. A causal bond graph of the multicellular serial converter

Input-output relation of the source commutation cell :

$$\begin{pmatrix} f_1 \\ f_2 \\ e_{2,1} \\ e_{3,1} \end{pmatrix} = \begin{pmatrix} 0 & 0 & -1+\rho_s & -\rho_s \\ 0 & 0 & \rho_s & -\rho_s \\ 1-\rho_s & \rho_s & 0 & 0 \\ -\rho_s & \rho_s & 0 & 0 \end{pmatrix} \begin{pmatrix} e_1 \\ e_2 \\ f_{2,1} \\ f_{3,1} \end{pmatrix} \tag{16}$$

Input-output relation of the i^{st} commutation cell :

$$\begin{pmatrix} f_{1,i} \\ f_{2,i} \\ f_{3,i} \\ e_{4,i} \\ e_{5,i} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & -\rho_i & -(1-\rho_i) \\ 0 & 0 & 0 & 1-\rho_i & -(1-\rho_i) \\ 0 & 0 & 0 & -\rho_i & \rho_i \\ \rho_i & 1-\rho_i & \rho_i & 0 & 0 \\ -(1-\rho_i) & 1-\rho_i & \rho_i & 0 & 0 \end{pmatrix} \begin{pmatrix} e_{1,i} \\ e_{2,i} \\ e_{3,i} \\ f_{4,i} \\ f_{5,i} \end{pmatrix} \tag{17}$$

Input-output relation of the load commutation cell :

$$\begin{pmatrix} f_{4,k} \\ f_{5,k} \\ e_5 \end{pmatrix} = \begin{pmatrix} 0 & 0 & \rho_c \\ 0 & 0 & -(1-\rho_c) \\ \rho_c & 1-\rho_c & 0 \end{pmatrix} \begin{pmatrix} e_{4,k} \\ e_{5,k} \\ f_5 \end{pmatrix} \tag{18}$$

with respectively, the control variables ρ_s, ρ_i and ρ_c.

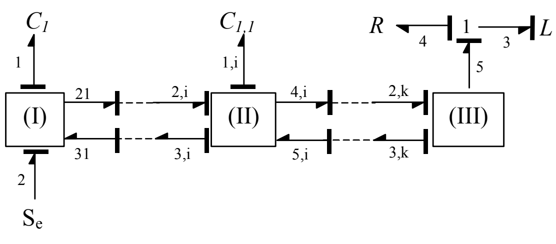

Fig. 5. The causal bond graph with the commutation cells blocks

An equivalent representation of the bond graph of figure 4 can be given by the structure represented figure 5. One time the input/output relations of the commutation cells determined (cf. equations (16) to

(18)), we have to aggregate them in order to deduce the global input/output relations (cf. relation (2)) allowing the determination of the state equation by inserting the constitutive laws.

- For the source commutation cell, we have :

$$f_1 = \left(-1+\rho_s\right) f_{2,1} - \rho_s\, f_{3,1} \qquad (19)$$

$$\begin{pmatrix} f_{2,1} \\ f_{3,1} \end{pmatrix} = \prod_{i=1}^{k} \begin{pmatrix} 1-\rho_i & -\left(1-\rho_i\right) \\ -\rho_i & \rho_i \end{pmatrix} \begin{pmatrix} f_{4,k} \\ f_{5,k} \end{pmatrix} \qquad (20)$$

$$f_{4,k} = \rho_c f_5 \qquad (21)$$

$$f_{5,k} = -\left(1-\rho_c\right) f_5 \text{ and } f_5 = f_3 \qquad (22)\text{-}(23)$$

Since :

$$\prod_{i=1}^{k} \begin{pmatrix} 1-\rho_i & -\left(1-\rho_i\right) \\ -\rho_i & \rho_i \end{pmatrix} = \begin{pmatrix} 1-\rho_1 & -\left(1-\rho_1\right) \\ -\rho_1 & \rho_1 \end{pmatrix} \qquad (24)$$

we finally obtain :

$$f_1 = \left(-1+\rho_s+\rho_1\right) f_3 \qquad (25)$$

- For the *k-1* elementary commutation cells, with $i = 1, 2, ..., k-1$:

$$f_{1,i} = -\rho_i\, f_{4,i} - \left(1-\rho_i\right) f_{5,i} \qquad (26)$$

Since (cf. figure 4) :

$$\begin{pmatrix} f_{2,i+1} \\ f_{3,i+1} \end{pmatrix} = \begin{pmatrix} f_{4,i} \\ f_{5,i} \end{pmatrix} \qquad (27)$$

From (20) and (24), it can be deduced that :

$$f_{1,i} = \left(-\rho_i \quad -\left(1-\rho_i\right)\right) \begin{pmatrix} 1-\rho_{i+1} & -\left(1-\rho_{i+1}\right) \\ -\rho_{i+1} & \rho_{i+1} \end{pmatrix} \begin{pmatrix} \rho_c \\ -\left(1-\rho_c\right) \end{pmatrix} f_3 \qquad (28)$$

Thus, finally :

$$f_{1,i} = \left(\rho_{i+1} - \rho_i\right) f_3 \qquad (29)$$

- For the k^{st} elementary commutation cell :

$$f_{1,k} = -\rho_k\, f_{4,k} - \left(1-\rho_k\right) f_{5,k} \qquad (30)$$

So :

$$f_{1,k} = \left(1-\rho_k-\rho_c\right) f_3 \qquad (31)$$

- For the load commutation cell :

From a general point of view,

$$e_3 = \sum_{i=1}^{k} \alpha_{1,i}\, e_{1,i} + \alpha_3\, f_3 + \alpha_1\, e_1 + \alpha_2\, e_2 + \alpha_4 e_4 \qquad (32)$$

Since S_{11} is a skew symmetric matrix, only two coefficients α_2 and α_4 are unknown (the others being deduced from relation (25), (29) and (31)). From figure (5) and relation (18), we have :

$$e_3 = \rho_c\, e_{4,k} - \left(1-\rho_c\right) e_{5,k} - e_4 \qquad (33)$$

using (17), it remains that :

$$\begin{pmatrix} e_{4,k} \\ e_{5,k} \end{pmatrix} = \begin{pmatrix} \rho_k \\ \rho_k - 1 \end{pmatrix} e_{1,k} + \sum_{i=k}^{2} \begin{pmatrix} 1-\rho_j & \rho_j \\ 1-\rho_j & \rho_j \end{pmatrix} \begin{pmatrix} \rho_{j-1} \\ \rho_{j-1}-1 \end{pmatrix} e_{1,j-1} + \left[\prod_{j=k}^{1} \begin{pmatrix} 1-\rho_j & \rho_j \\ 1-\rho_j & \rho_j \end{pmatrix}\right] \begin{pmatrix} 1-\rho_s & \rho_s \\ -\rho_s & \rho_s \end{pmatrix} \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} \qquad (34)$$

Since :

$$\prod_{j=k}^{1} \begin{pmatrix} 1-\rho_j & \rho_j \\ 1-\rho_j & \rho_j \end{pmatrix} = \begin{pmatrix} 1-\rho_1 & \rho_1 \\ 1-\rho_1 & \rho_1 \end{pmatrix} \qquad (35)$$

From (33) and (34) and (35), it can be deduced that :

$$\alpha_2 = \rho_s \qquad (36)$$

$$\alpha_4 = -1 \qquad (37)$$

At least :

$$f_4 = f_3 \qquad (38)$$

Relations (25), (29), (31), (36), (37) and (38) allow to determine the S_{ij} matrices and thus the implicit standard form (cf. relation (2)),we finally obtain that :

$$Z^T = \left(f_1 \quad f_{1,1} \quad ... \quad f_{1,k-1} \quad f_{1,k} \quad e_3\right) \qquad (39)$$

$$X^T = \left(q_1 \quad q_{1,1} \quad ... \quad q_{1,k-1} \quad q_{1,k} \quad p_3\right) \qquad (40)$$

$$D_i = \left(e_4\right) \text{ and } U = \left(e_2\right) \qquad (41)\text{-}(42)$$

$$S_{11} = \begin{pmatrix} 0 & 0 & \cdots & 0 & 0 & \rho_s+\rho_1-1 \\ 0 & 0 & \cdots & 0 & 0 & \rho_2-\rho_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \rho_k-\rho_{k-1} \\ 0 & 0 & \cdots & 0 & 0 & 1-\rho_k-\rho_c \\ 1-\rho_1-\rho_s & \rho_1-\rho_2 & \cdots & \rho_{k-1}-\rho_k & \rho_k-\rho_c-1 & 0 \end{pmatrix}$$

$$S_{13} = \left(0 \quad ... \quad 0 \quad -1\right)^T, \; S_{15} = \left(0 \quad ... \quad 0 \quad \rho_s\right) \qquad (43)\text{-}(45)$$

Matrices S_{33} and S_{35} are null scalars. As mentioned in §2.2., a generic state equation, available for all valid modes, can be deduced. For the present case, we obtained as state equation (deduced from (8)):

$$\begin{pmatrix} \dot{q}_1 \\ \dot{q}_{1,1} \\ \vdots \\ \dot{q}_{1,k} \\ \dot{p}_3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & \cdots & 0 & 0 & \frac{\rho_s+\rho_1-1}{L} \\ 0 & 0 & \cdots & 0 & 0 & \frac{\rho_2-\rho_1}{L} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \frac{\rho_k-\rho_{k-1}}{L} \\ 0 & 0 & \cdots & 0 & 0 & \frac{1-\rho_k-\rho_c}{L} \\ \frac{1-\rho_1-\rho_s}{C_1} & \frac{\rho_1-\rho_2}{C_{1,1}} & \cdots & \frac{\rho_{k-1}-\rho_k}{C_{1,k-1}} & \frac{\rho_k+\rho_c-1}{C_{1,k}} & -\frac{R}{L} \end{pmatrix} \begin{pmatrix} q_1 \\ q_{1,1} \\ \vdots \\ q_{1,k} \\ p_3 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ \rho_s \end{pmatrix} E \qquad (46)$$

4.3 The Generic Passivity Based Controller For A multicellular Serial converter

In order to determine the passivity based controller, we just have to apply relations (14) and (15) on this particular application. The objective being to control the voltage in the capacitors and the current in the load, the output equation variables are represented by the *Z* vector. Since X_c does not depend on ρ , the controller will be a static state feeback (cf.relation (47)). This equation defines a system of $k+2$ equations with $k+2$ unknowns variables (the control variables).

$$-\begin{pmatrix} \frac{\varepsilon_1}{C_1} & 0 & \cdots & 0 & 0 & 0 \\ 0 & \frac{\varepsilon_2}{C_{1,1}} & \cdots & 0 & & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \frac{\varepsilon_{k-1}}{C_{1,k-1}} & 0 & 0 \\ 0 & 0 & \cdots & 0 & \frac{\varepsilon_k}{C_{1,k}} & 0 \\ 0 & 0 & \cdots & 0 & 0 & \frac{\varepsilon_{k+1}}{L} \end{pmatrix} \begin{pmatrix} q_1 - q_{1c} \\ q_{1,1} - q_{1,1c} \\ \vdots \\ q_{1,k-1} - q_{1,k-1c} \\ q_{1,k} - q_{1,kc} \\ p_3 - p_{3c} \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ \rho_s \end{pmatrix} E =$$

$$\begin{pmatrix} 0 & 0 & \cdots & 0 & 0 & \frac{\rho_s + \rho_1 - 1}{L} \\ 0 & 0 & \cdots & 0 & 0 & \frac{\rho_2 - \rho_1}{L} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \frac{\rho_k - \rho_{k-1}}{L} \\ 0 & 0 & \cdots & 0 & 0 & \frac{1 - \rho_k - \rho_c}{L} \\ \frac{1-\rho_1-\rho_s}{C_1} & \frac{\rho_1 - \rho_2}{C_{1,1}} & \cdots & \frac{\rho_{k-1} - \rho_k}{C_{1,k-1}} & \frac{\rho_k + \rho_c - 1}{C_{1,k}} & \frac{R}{L} \end{pmatrix} \begin{pmatrix} q_{1c} \\ q_{1,1c} \\ \vdots \\ q_{1,k-1c} \\ q_{1,kc} \\ p_{3c} \end{pmatrix} \qquad (47)$$

5. A PARTICULAR CASE : THE 3 LEVEL MULTICELLULAR SERIAL CONVERTER

From the results of the previous section, the equation of the controller for this 3 level multicellular serial is:

$$\begin{pmatrix} \rho_s \\ \rho_1 \\ \rho_c \end{pmatrix} = -\frac{1}{f_{3c} E} \begin{pmatrix} e_{1c} & e_{1,1c} & f_{3c} \\ E - e_{1c} & -e_{1,1c} & -f_{3c} \\ -E + e_{1c} & -E + e_{1,1c} & f_{3c} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} \qquad (49)$$

$$\begin{cases} \alpha = -\varepsilon_1 \left(e_1 - e_{1c}\right) + f_{3c} \\ \beta = -\varepsilon_2 \left(e_{1,1} - e_{1,1c}\right) - f_{3c} \\ \gamma = -\varepsilon_3 \left(f_3 - f_{3c}\right) - e_{1c} + e_{1,1c} + R f_{3c} \end{cases}$$

A simulation with Matlab-Simulink has been realized using a PWM at 500Hz with the following damping parameters :

$\varepsilon_1 = 37500$, $\varepsilon_2 = \varepsilon_3 = 0.475$

and physical parameters :

$C_1 = C_2 = 1mF$, $L_b = 0.075H$, $R = 20\Omega$, $E = 90V$

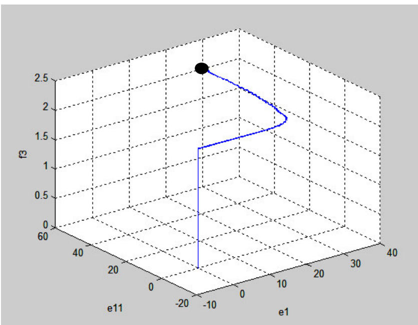

Fig. 6. Trajectory in the output space

The initial state is the null state the control objective is so that : $Y_c = \begin{pmatrix} 30 & 60 & 2 \end{pmatrix}^T$. The control objective is achieved in less than 10 ms.

5. CONCLUSION

In this article Passivity Based Control has been successfully achieved on a generic multicellular serial converter. The methodology is based on bond graph formalism and the notion of commutation cells that allows the generalization whatever the number of cells. Furthermore, simulation results show that PBC is an efficient method to control non linear system with switching components. At least, such an approach can be applied on other multicellular structures (for example the parallel structure).

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