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Sliding mode and fault tolerant control for multicell converter four quadrants

S. Meradi[a,*], K. Benmansour[b], K. Herizi[a], M. Tadjine[a], M.S. Boucherit[a]

[a] Laboratoire de Commande des Processus, Département de génie électrique, Ecole nationale polytechnique10, Avenue Pasteur, Hassen Badi, El-Harrach, Alger, Algeria
[b] Equipe de Commande des Systèmes (E.C.S.) – E.N.S.E.A, France

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ABSTRACT

In this paper, we present a multicell converter connected to a load R-L. We show its importance in the practical implementation of a sliding mode control algorithm. The validity of the controller is shown with simulation results. In the second part a topology with fault tolerant control of multicell converters is proposed. This topology is developed through analysis of different power device's failure modes. Our objective is to present a methodology for the diagnosis of the faults in cells by using an sliding mode observer. The generation of residue is used to know the indicators of the faults. Simulation results are presented in order to illustrate the performance of the proposed approach.

1. Introduction

In the last five decades, control system methodologies have evolved from simple mechanical feedback structures into sophisticated and advanced electronic devices for controlling high performance and highly unstable systems which optimize cost and control effort. Some of these control methodologies, for example the 'three term' PID (proportion, integral and derivative) controller [1,4,5,14,20–24] and the Kalman filter [2], have found success in industry with a wide range of applications.

The performances of static electronic power converters have been evolving through the last decades, in an attempt to be more reliable and efficient. These high performances are directly linked to the converter's architecture and its internal electronic components. In effect, the losses due to the commutation of the power semiconductors are proportional to the transited current, at the chopping frequency and the voltage across terminals. First, the "skin effect" necessitates an increase of the voltage and hence reduces the current circulating in the system during a power rise. Next, the semiconductors currently used in power electronics are most efficient and cheapest when the employed voltage is low and the circulating current is low. Finally, a low chopping frequency might reduce the number of commutation of a switch and hence to reduce the commutation losses and at the same time increase their life span.

Multicell converters are currently embedded in all electric devices. Their aim is to convert an electrical energy shape (voltage/current/frequency) to another one. For industrial applications with a few megawatts power, voltages in the switching components become very high (several kilovolts) and sometimes, switches cannot support these voltage values.

The serial multicell converter enables to realize a safe assembly of power electronics components in cascade operating in commutation [6]. This new approach presents two additional advantages: the possibility of a modular construction and the possibility of using components having large diffusion.

In this work, we will apply a sliding mode controller to the load R-L connected to a multicell converter. This control is very well adapted for this kind of converter, as we shall demonstrate in the subsequent sections.

Sliding modes based controllers have witnessed major development these last years. Such an interest in sliding modes controllers can be explained by their intrinsic robustness property and the relative ease of application (see for example [6,8–10,16,18,19]). The main objective of this paper is to show that the multicell converter is very well suited for a control set-up using sliding modes.

The multicell converter are very sensitive to the failure of the power semiconductors, The analysis of faults can be focused on the multicell converter cell, as this unit has the most failure sensitive components. It would decrease the performances of the system and would oblige it to disconnect itself from the network. Moreover, if the fault is not detected quickly and then not compensated, it can lead to the destruction of the converter. Thus to reduce these risks, one detection of the faults as well as an insulation and one accommodation of the fault must be implemented very quickly so

* Corresponding author. Tel.: +213 661981798.
E-mail addresses: smeradi@yahoo.fr (S. Meradi), k_benmansour@yahoo.fr (K. Benmansour).

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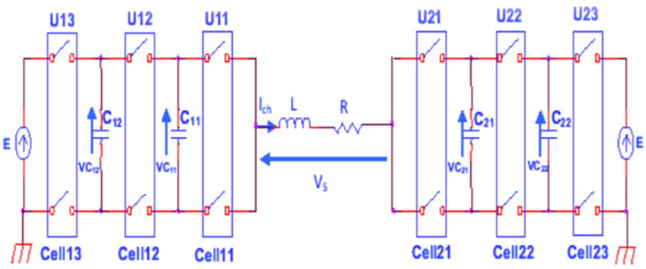

Fig. 1. Multicell converter.

that the multicell converter can continue to function under nominal conditions, while waiting for a future maintenance action.

In this paper we are interested in the use of advanced automatic observers in the diagnosis with an application to multicell converters. This technique uses, for the generation of residue, a state observer which we provided estimated quantities. These quantities will then be compared to the sizes available in the real system to generate our residual signal which allow us to detect a possible fault. These methods are then applied in the diagnosis of multicell converters to three cells.

The paper is organized as follows. In Section 2, the physical model of the multi-cellular converter three cells is discussed. In Section 3, we develop the PWM control of the converter and derive the sliding mode control properties of the state vector in Section 4. Sliding mode control of multicell converter is presented in Section 5. Finally, in Section 6 a fault tolerant control topology of multicell converter integrating a hardware solution are proposed.

2. Modelling of the multicell converter

The multicell converter is a variable structure system which changes during its operation. It is characterized by the choice of a function and switching or commutation logic. This choice enables the system to switch from one structure to another at every instant of time.

Fig. 1 depicts the topology of a multicell converter four quadrants commutation cells [8]. Each cell is controlled by a binary function $u_k(t)$. The association of the independent voltage source, converter and load constitutes a hybrid system. But here we must note that the converter itself is intrinsically hybrid system due to the presence of switches and capacitors (V_{Ck} continuous variables).

Each cell has to bear the voltage $(V_{\text{cell}})_k$ with:

$$(V_{\text{cell}})k = (V_{Ck} - V_{Ck-1}) \quad \text{for } k = 0, \ldots, n$$

with $V_{C_0} = 0$ and $V_{C_p} = V_{\text{source}}$.

On the other hand, an equal distribution of the voltage constraints on each cell induces the $(p-1)$ input references:

$$V_{C_i} = i\frac{V_{\text{source}}}{p} \quad \text{for } i = 1, \ldots, n-1$$

In addition, the applied voltage to the load is given by:

$$V_{\text{charge}}(t) = \sum_{k=1}^{n} u_k V_{\text{cell}_k} \tag{1}$$

We create $(n+1)$ distinct levels $\ell(V_{\text{source}}/p)$ with ℓ=0, . . ., n. The ℓth level is achieved by setting ℓ cells among n to "1". Note that all the combinations are potentially required to realize a particular level. The voltages across the terminals of the capacitors are given by:

$$C_k \frac{dV_{C_k}}{dt} = I_{\text{charge}}(u_{k+1} - u_k) \quad \forall k = 1, \ldots, n-1$$

Our structure (Fig. 1) is made of two legs, each leg consisting of 3 cells. Thus we have 6 controls signals determining the state of the converter and the output voltage has seven levels: $\{-E, -2E/3, -E/3, 0, E/3, 2E/3, E\}$.

Each leg can be controlled independently. Hence, each leg has to supply the necessary voltage in order to obtain the required value at the converter output.

The dynamics of the converter used is given by:

$$\begin{aligned}
\dot{V}_{C11} &= \frac{1}{C_{11}} \cdot (u_{12} - u_{11}) \cdot I_{\text{ch}} \\
\dot{V}_{C12} &= \frac{1}{C_{12}} \cdot (u_{13} - u_{12}) \cdot I_{\text{ch}} \\
\dot{V}_{C21} &= \frac{1}{C_{21}} \cdot (u_{22} - u_{21}) \cdot I_{\text{ch}} \\
\dot{V}_{C22} &= \frac{1}{C_{22}} \cdot (u_{23} - u_{22}) \cdot I_{\text{ch}} \\
\dot{I}_{\text{ch}} &= -\frac{R}{L} \cdot I_{\text{ch}} + \frac{1}{L} \cdot V_S \\
V_S &= (u_{13} - u_{23})E + (u_{11} - u_{12})V_{C11} + (u_{11} - u_{12})V_{C12} \\
&\quad - (u_{21} - u_{22})V_{C21} - (u_{23} - u_{22})V_{C22}
\end{aligned} \tag{2}$$

The aim of the developed control is twofold: on the one hand, it has to ensure the balancing of the voltage across the floating capacitors. On the other hand, the level of voltage required at the output has to be achieved. The characteristics of series multicellular converter provide the possibility to ensure the balance and the evolution of the voltage across the capacitors by acting directly on the converter control signal.

First, it is necessary to know all the possible states of the converter and the evolution of the voltage across the floating capacitors and the output converter's voltage level for each state.

3. PWM control of multicell converter

There is a control open loop very simple to ensure the stability of this converter. It is known as the control PWM (modulation of width of pulse).

The control by PWM is cutting output voltage generated by the converter in a series of basic reasons of period very low [6]. The levels of control in each cell are generated by the intersection between a triangular carrier and signal modulating (constant in the case of a chopper and sinusoidal in the case of a UPS) [17]. The control by PWM requires as many triangular carriers that cell in order there. In addition, carriers are all regularly lagged between them by a δ angle. The equations to generate triangular signal rated tr_k on the interval [0,1] are [12]:

$$\begin{aligned}
tr_1 &= \frac{\arcsin(\sin(2\pi f_p t - \varphi)) + \pi/2}{\pi} \\
tr_2 &= \frac{\arcsin(\sin(2\pi f_p t - \varphi - \delta)) + \pi/2}{\pi} \\
&\vdots \\
tr_p &= \frac{\arcsin(\sin(2\pi f_p t - \varphi - (p-1)\delta)) + \pi/2}{\pi}
\end{aligned} \tag{3}$$

If the φ angle present in the system of Eq. (3) is equal to $\pi/2$, the triangular signal will be centered on the half period of the carrier (thus the half period of cutting). Our converter is intended for the feeding of a current machine continuous, so it is a chopper four quadrants. The modulating signal is constant. Fig. 2 gives the synoptic control loop opened by a chopper pulse width modulation four quadrants.

We can therefore draw the following properties generalizing p cells of switching [19]: