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# Bandwidth and maximum switching frequency of multicell converters

R.Ameur, M.Fadel, T.Meynard  
LEEI UMR-CNRS 5828, INPT  
2, Rue Charles Camichel B.P. 7122, 31071  
Toulouse CEDEX 7, France  
Tel. : +33.05.61.58.82.08, Fax. : +33.05.61.63.88.75  
e-mail : [ameur@leei.enseeiht.fr](mailto:ameur@leei.enseeiht.fr)  
URL : <http://www.leei.enseeiht.fr>

## Keywords

Multilevel converters, converter control, sliding mode control.

## Abstract

In this paper, the authors focus on the evaluation of the bandwidth of the series multicell converter. A method to determine the theoretical limit of the operational frequency is presented. Several control laws using a constant switching frequency are proposed and compared. The final aim is to realize a control law which has the maximum bandwidth.

## Introduction

Due to their high performance, multicell converters are increasingly being employed in a wide range of applications [1]. It has been shown that sliding mode control of these converters allows for a good dynamic performance (both response speed and robustness) [2]. The aim of this paper is to show that it is possible to reach the dynamic limits of a multicell converter using a sliding mode control strategy. To start, a method to determine the limit of the operational frequency is presented. Afterward, a sliding mode control and a non-interactive control are described. Lastly, a comparison between the control strategies, based on simulation results, is presented.

For a  $p$ -cell single-phase inverter supplying a passive RL load, the problem is to find the maximum frequency for a sinusoidal reference current that can be imposed for a given amplitude and maximum ripple current.

## Determination of the operation point limit

Let us consider here a  $p$ -cell converter supplying a passive load RL on which the current must be imposed (Fig. 1).

In this section we will present a method to determine the couple of limit values, characterized by the amplitude and the maximum frequency of the reference current that can be reached exploiting all the possibilities of the conversion structure and by admitting a limited error. This couple of values is called the limit operation point.

## Dimensioning

To characterise the bandwidth of a multicell converter, we will assume a fixed switching frequency  $f_d$  which is given in the specifications converter. The table (I) represents the converter specifications. The dimensioning of the load inductor- is done by fixing

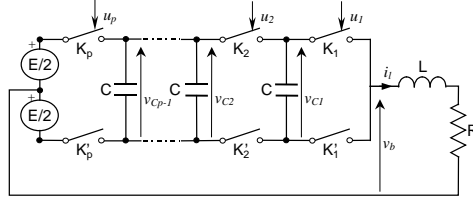


Fig. 1- Structure of a p-cell inverter

a maximum current ripple  $\Delta i_{max}$ . For the dimensioning of the floating capacitors, the maximum ripple voltage  $\Delta v_{Cmax}$  is fixed too.

$$L = \frac{E}{4p^2 f_d \Delta i_{max}} = \frac{R}{4p^2 f_d} \Delta i_{max} \% \quad (1)$$

$$C = \frac{I_{max}}{p f_d \Delta v_{Cmax}} \quad (2)$$

$E = 900V$	$p = 3$	$f_d = 16kHz$
$R = 20\Omega$		$I_{max} = \frac{E}{2R}$
$\Delta i_{max} = \Delta i_{max} \% \cdot (2 \cdot I_{max})$		$L = 0.69mH$
$\Delta v_{Cmax} = \Delta v_{Cmax} \% \cdot (E)$		$C = 23.5\mu F$

Table I- Converter specifications.

## Analysis

The operation point limit is represented by the couple  $(I_m, f_m)$ . Where,  $I_m$  is the amplitude of the reference current and  $f_m$  the maximum operation frequency. This operation point limit depends on the converter parameters, witch are the source voltage and the load parameters. All these parameters characterise the dimensioning of the conversion structure. This operation limit could be reached by certain control strategies.

The maximum dynamic of the converter is obtained when all the top (resp. bottom) switches are closed for an increasing (resp. decreasing) current. This limit operation corresponds to a classical two level converters operation since the output voltage switches between  $-\frac{E}{2}$  and  $\frac{E}{2}$ .

For a maximum positive current slope, the output voltage is  $\frac{E}{2}$ . The load current is thus :

$$i_l(t) = \frac{E}{2} (1 - e^{-t/\tau}) \quad (3)$$

with  $\tau = \frac{L}{R}$ .

The reference current is :

$$i_{ref}(t) = I_m \sin(2\pi f_m t) \quad (4)$$

In order to have a good tracking of the reference current, it is necessary to check relation

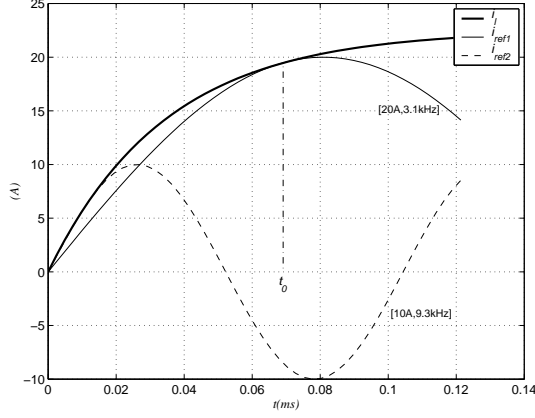


Fig. 2- Principle used to solve (6)

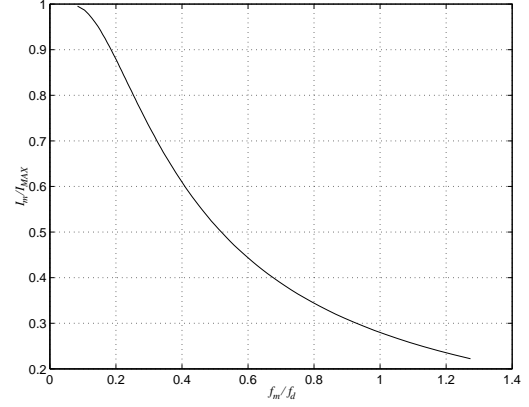


Fig. 3- Characteristic of  $\frac{f_m}{f_d} = g\left(\frac{I_m}{I_{max}}\right)$

(5).

$$i_l(t) \geq i_{ref}(t) \quad ; \quad \forall t \in [0, \frac{1}{4f_m}] \quad (5)$$

By replacing the expressions of  $i_{ref}$  and  $i_l$ , we obtain at the limit operation point the relation (6).

$$\begin{aligned} \frac{E}{2}(1 - e^{-t_0/\tau}) &= I_m \sin(2\pi f_m t_0) \\ t_0 &\in [0, \frac{1}{4f_m}] \end{aligned} \quad (6)$$

It is an equation with three variables; the amplitude of reference current  $I_m$ , the theoretical limit frequency  $f_m$  and the time  $t_0$ . The use of a numerical tool to solve the equation (6) leads us to the characteristic  $\frac{I_m}{I_{max}} = g(\frac{f_m}{f_d})$  (Fig. 3).

Figure (2) illustrates the determination of two operation limits for two different current amplitudes  $(I_{m1}, f_{m1})$  and  $(I_{m2}, f_{m2})$ .

*Discussion :* In this curve, we note that for lower amplitudes of the reference current, the limit frequency is bigger. Note that  $f_m$  corresponds to the theoretical maximum frequency which cannot exceed independently of the controls strategy. However, this limit cannot be reached with all the control laws.

In order to reach the switching frequency  $f_d$ , the reference current amplitude must not exceed 28% of the maximum current  $I_{max}$  (Fig. 3).

### Influence of the cell number $p$

The cell number  $p$  influences the limit frequency. To show this, let's consider two multicell converters  $Conv_1$  with  $p_1$  cells and  $Conv_2$  with  $p_2$  cells, each one supplying RL load. For the same fixed ripple current, the load inductor values are different.

For the same reference current amplitude ( $I_{mo}$ ) in both converters, the limit frequency is proportional to the cell number.

According to (6), we have :

$$\begin{aligned}\frac{E}{2}(1 - e^{-(t_1/\tau_1)}) &= I_{mo}\sin(2\pi f_{m1}t_1) \\ \frac{E}{2}(1 - e^{-(t_2/\tau_2)}) &= I_{mo}\sin(2\pi f_{m2}t_2)\end{aligned}\quad (7)$$

The term  $I_{mo}\sin(2\pi f_{mi}t_i)$  is the value of the reference current at the intersection time

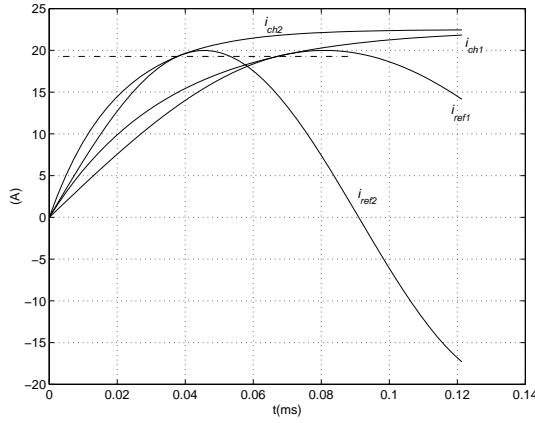


Fig. 4- Effect of inductor variation on the limit frequency

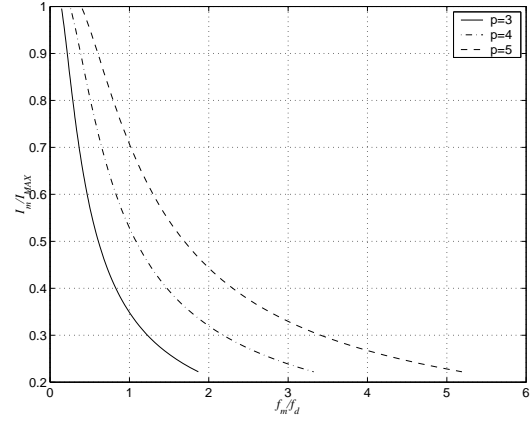


Fig. 5- Influence of the cell number on the characteristic  $\frac{f_m}{f_d} = g\left(\frac{I_m}{I_{m,ax}}\right)$

between the load current and its reference. This value depends only on the reference current amplitude.

According to figure (4), we find :  $f_{m1}t_1 = f_{m2}t_2$ .

From there and using (7), we deduce :

$$\frac{f_{m2}}{f_{m1}} = \frac{\tau_1}{t_2} \Rightarrow f_{m2} = \left(\frac{p_2}{p_1}\right)^2 f_{m1} \quad (8)$$

The limit frequency is thus proportional to the square of the cell number. To obtain good dynamic performances we must therefore increase the cell number. If we like to obtain a limit operation until the switching frequency ( $\frac{f_{m2}}{f_d} = 1$ ), on all the range of variation of the reference current amplitude , it is necessary to have  $p_2 = 7$ .

## Sliding mode control

### Switching functions

Consider the  $p$ -cell converter of the figure (1). The converter control is a sliding mode strategy with fixed switching frequency. This control law consists in defining  $p$  switching functions to drive the  $p$  top switches of the converter. The  $p$  bottom switches are obviously complementary.

The switching functions are obtained by using the sliding mode theory [2] and are given by (9). To impose a fixed switching frequency, a  $PI$  controller and a modulator are

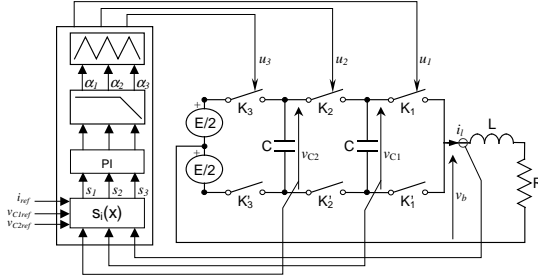


Fig. 6- Single-phase three-cell inverter controlled in sliding mode with fixed frequency

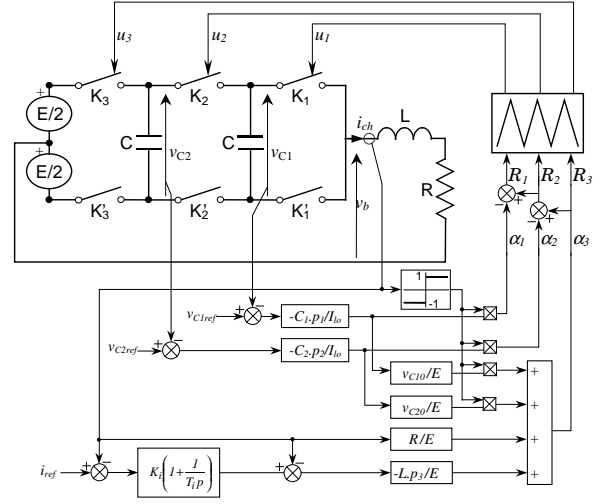


Fig. 7- Structure of the linear decoupling control with PI corrector for the current loops

associated to each switching function. A second order filter is also used to suppress high order harmonics (figure (6) ).

$$s_i : \begin{cases} s_1 = 3i_{ref} \frac{v_{C1}}{E} - i_l \\ s_2 = 3i_{ref} \frac{v_{C2} - v_{C1}}{E} - i_l \\ \vdots \\ s_k = 3i_{ref} \frac{v_{Ck} - v_{Ck-1}}{E} - i_l \\ \vdots \\ s_p = 3i_{ref} \frac{E - v_{Cp-1}}{E} - i_l \end{cases} \quad (9)$$

## Non-interactive control

The non-interactive control strategy used here is the linear decoupling control [5]. The linearization has been achieved around the converter steady-state operation point  $(I_{l0}, v_{c10}, v_{c20})$ . The decoupling consists of an algebraic state feedback as it is shown in figure (7). We then obtain three independent linear systems. The three independent states are then be controlled using classical linear controller (P regulator for the voltages control loops and PI regulator for the current control loop).

## Simulation results

The results presented here, are obtained with sliding mode control using a fixed switching frequency for a reference current amplitude of 10A (Fig. 8) and 20A (Fig. 9). The frequency of the reference current used in these simulations is the limit frequency.

Note that in both cases, the track of the reference current is assured and the balancing of the floating capacitor voltages is fast. Note also that the converter saturates when the current reaches its limit values ( $-I_{max}$ ,  $I_{max}$ ). The sliding mode control has a good

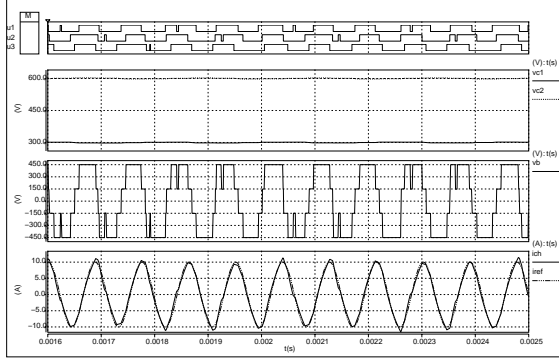


Fig. 8- Control signals, floating capacitor voltages, leg voltage and load current with  $I_m = 10A$ ,  $f_m = 9.30kHz$

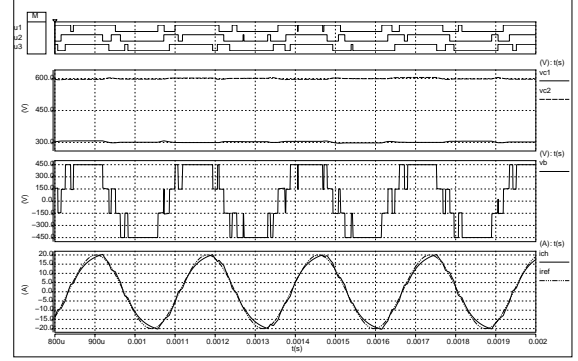


Fig. 9- Control signals, floating capacitor voltages, leg voltage and load current with  $I_m = 20A$ ,  $f_m = 3.11kHz$

bandwidth which can reach the theoretical limit operation frequency, i.e.  $f_{lim} = 3.11kHz$  and  $I_{max} = 20A$ .

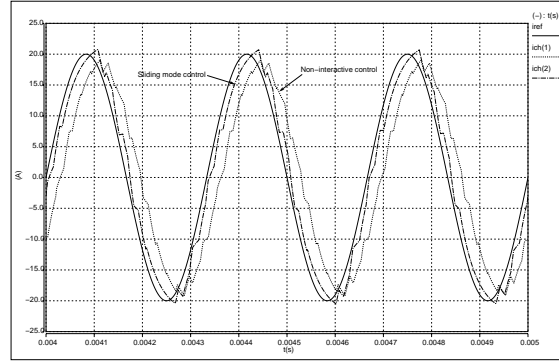


Fig. 10- The load current with both control strategies at the limit frequency

Figure (10) represents the response of the system for both sliding mode and non-interactive controls, with the same reference current.

The phase-shift between the load current and its reference is less significant with the sliding mode control strategy.

The decoupling control strategy introduces an important phase-shift and does not, therefore, allow a good reference tracking at the limit frequency. The decoupling slows-down the state variable evolution dynamics and thus limits the system bandwidth.

## Conclusion

The objective of the present paper is the study of the dynamic limit of the sliding mode control for series multicell converter. First, a method to determine the operational limit frequency is presented independently of the control strategy. It is then shown that this theoretical limit can be reached in simulation by the use of a sliding mode control law. Then, a non-interactive control and a the sliding mode control are comapred. It is shown

that the non-interactive control law does not allow to reach the theoretical limit operation. The sliding mode control appears therefore to be more performant since it exploits the maximum performances of the converter.

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