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Guillaume Gateau, Marco Rivera

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MPC Algorithms for Parallel MultiCell Converters

E. Solano, A. Llor, T. Meynard, M. Fadel, G. Gateau
Laboratoire PLASMA et Conversion d' Energie
(LAPLACE), Université de Toulouse FRANCE
Email: (solano, llor, meynard, fadel, gateau)@laplace.univ-tlse.fr

M. Rivera
Universidad de Talca
(LCEEP), Curicó, CHILE
Email: marcoriv@utalca.cl

Abstract—The parallel association of classical commutation cells is a good solution for increasing the output current driven by the converters while the classical semiconductors technology are used. The control strategies used with this type of connection must be able to ensure good distribution of the output current among the different legs. This paper applies two control strategies based on the Model Predictive Control (MPC) in order to handle these type of connections. A comparison between these control strategies is also carried out by experiments.

Index Terms—MultiCell converters, Model Predictive Control (MPC), InterCell transformers (ICT), Parallel converters.

NOMENCLATURE

V_{dc}	DC-link voltage
V_{out}	Output voltage
i_{mc}	Common output current
i_{md}	Differential current
L_f	Leakage inductance
L_m	Mutual inductance
i_1, i_2	Output phase 1 and 2 currents
R	Output phase 1 and 2 resistances
C	Output capacitor
R_l	Load resistance
V_1, V_2	Output voltage 1 and 2 phase
S_x	Switch of the commutation cell x, x=1,2
S_{nx}	Complementary switch of S_x

I. INTRODUCTION

The research of new power converters topologies using standard semiconductor devices has allowed the evolution of multilevel converters [1]. In this way, many topologies using high input voltages with several output voltage levels have been introduced. The parallel connection of commutation cells has also been used as a way to increase the power handled by the converter while the classical technology of switches is used. A higher output current with a lower ripple can be reached if the number of phases connected in parallel increases. The use of an InterCell Transformer (ICT) for carrying out this connection gives a lot of advantages, mainly in the phase currents because their ripple are reduced and their frequency are increased. This connection has recently been developed in different areas of energy conversion [2] [3] [4].

Many control strategies have been applied to parallel converters given its multilevel characteristic, these strategies are the same employed with multilevel converters over the last years [5]. In [1] a classification of these strategies around two main groups is presented: the state-space vector domain with the classical space vector modulation (SVM) strategy and the time domain strategies. In the time domain, many strategies using the extra degrees of freedom provided by the additional switching states and the classical PWM have been introduced. Among these strategies, we find the phase shifted(PS-PWM), the phase disposition (PD-PWM) and the phase opposition disposition (POD-PWM), etc. [1]

Model Predictive Control (MPC) [6] is a modern strategy which uses the mathematical model of the system to be controlled and also an optimization criterion for selecting the optimal state of the converter at each sampled time. A classification of the different predictive control strategies is presented in [6].

Different MPC strategies have been applied with the serial connection of commutation cells [7] [8]. This paper applies the classical MPC strategy and another strategy based in MPC with variable commutation instants for controlling the output current for the parallel connection of two commutation cells. The constraints of this topology concern mainly the good distribution of the output current among the two legs. The advantages and the drawbacks of each strategy are also presented.

II. PARALLEL CONNECTION OF COMMUTATION CELLS

A. Parallel connection

The parallel connection of commutation cells allows higher output currents using classical semiconductors devices. It can be implanted with separated inductors or inductors coupled magnetically, better known as InterCell Transformers (ICT). An ICT reduces the current ripple in the windings and decrease the flux swing in some regions of the core, obtaining thus a significant reduction of switching, copper and core losses [9].

The topology used in this paper and presented in Fig.1, it uses two commutation cells connected in parallel. Each commutation cell contains a pair of switches S_x and S_{nx} that must be always in complementary state. This connection can be made by using separated or coupled inductors. The

connection in Fig.1 is carried out via an ICT, represented by a transformer model with L_f and L_m describing the leakage and the magnetic inductance, respectively.

The number of possible states for the studied topology (N possible states in each cell and n cells connected in parallel) is:

$$N^n = 2^2 = 4.$$

These states are presented in Table I where S_x is 1 when the switch is ON and 0 when is OFF.

TABLE I: States of two commutation cells connected in parallel

State	S_1	S_2	V_1	V_2	V_{mc}	V_{md}
0	0	0	0	0	0	0
1	0	1	0	V_{dc}	$V_{dc}/2$	$V_{dc}/2$
2	1	0	V_{dc}	0	$V_{dc}/2$	$-V_{dc}/2$
3	1	1	V_{dc}	V_{dc}	V_{dc}	0

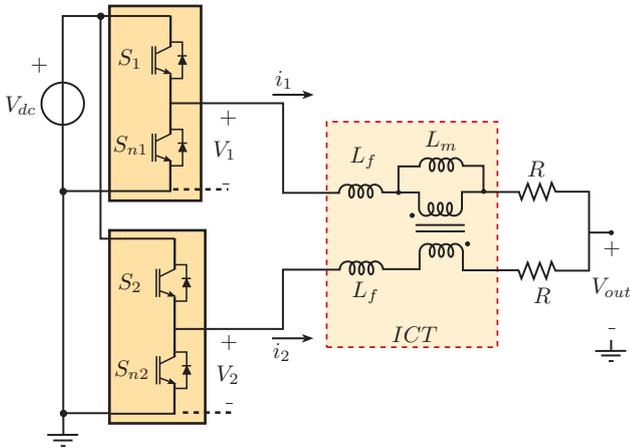


Fig. 1: Two commutation cells connected in parallel

III. MATHEMATICAL MODEL

A. Parallel connection

The study of the parallel connection, especially when an ICT is used can be simplified if a common/differential model is used [10]. The common mode (Fig.2(a)) describes the current flowing through the load i_{mc} whereas the differential mode (Fig.2(b)) reflects the nonuniform distribution of the output current among the different legs connected in parallel. These models are obtained from equations describing each leg connected in parallel and they are represented by the equations (1) and (2).

The voltages V_1 and V_2 are function of the switching states and the input voltage V_{dc} . For V_1 we have:

$$V_1 = \frac{(S_1 + S_2) * V_{dc}}{2},$$

$$V_{mc} - V_{out} = \frac{L_f}{2} \frac{di_{mc}}{dt} + \frac{R}{2} i_{mc}, \quad (1)$$

where:

$$V_{mc} = \frac{V_1 + V_2}{2}; \quad i_{mc} = i_1 + i_2.$$

$$V_{md} = (L_f + 2 * L_m) \frac{di_{md}}{dt} + R_{1,2} i_{md}, \quad (2)$$

where:

$$V_{md} = \frac{V_1 - V_2}{2}; \quad i_{md} = \frac{i_1 - i_2}{2}.$$

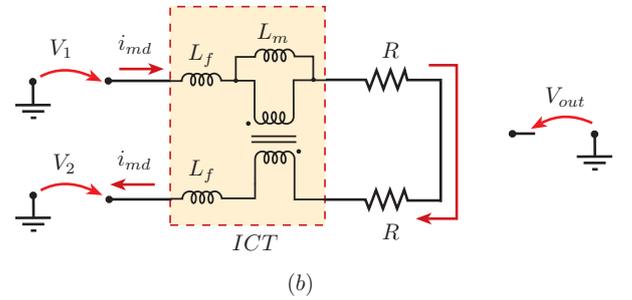
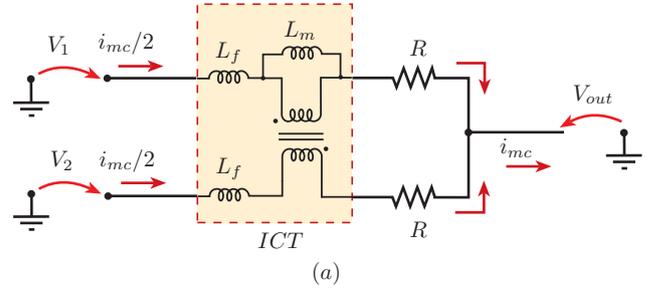


Fig. 2: (a) Common mode circuit ; (b) Differential mode circuit

IV. MODEL PREDICTIVE CONTROL MPC STRATEGY

MPC uses the mathematical model of the system for predicting at each sampling instant k , the behavior of the system at $k + 1$. The prediction is carried out with the measurements and the forward Euler approximation used to get the discrete system from equations (1) and (2). The selection of the next state is carried out by minimizing a cost function g , evaluated at each sampling instant T_s for all the states. Normally, this function contains several terms with the difference between the reference and the predicted values of the variables at each $k + 1$ instant. Other term representing some specific request, such as limitation of the switching frequency or nonlinearities can also be included.

Fig.2(a) shows the MPC scheme for controlling the proposed topology. Fig.2(b) presents the principle of the MPC strategy over a finite horizon.

A. Cost function

The cost function used to control the studied topology is presented in equation 3. The first and second terms of this equation represent the difference between the common and differential currents with their references. The third term is used to avoid a double commutation in the cells and it is

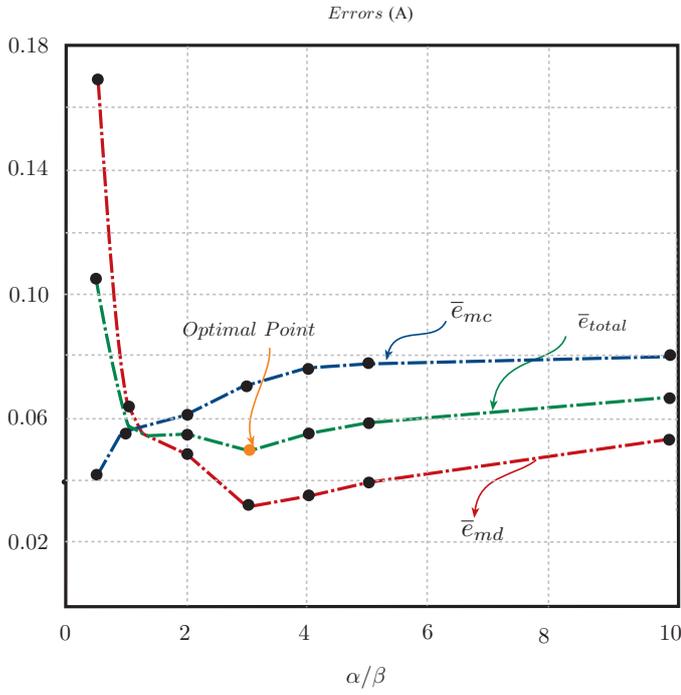


Fig. 4: Variation of \bar{e}_{total} with the ratio α/β

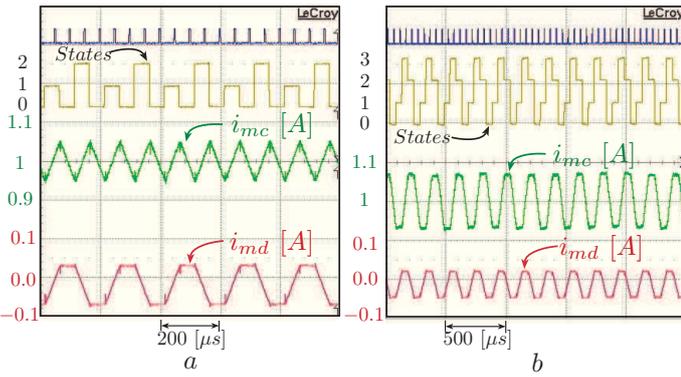


Fig. 5: Steady state response of the MPC strategy

simulations was $f_s = 20$ [kHz], thus the maximal switching frequency is around 10 [kHz] and the switching frequency of each commutation cell is limited to 5 [kHz]. The average frequency of the commutation cells is defined by the next equation.

$$\bar{f}_{comm} = \frac{1}{2} \sum_{cell=1}^2 \frac{\sum_{\Delta t} N_{cell}}{\Delta t}, \quad (5)$$

where N_{cell} represents the number of commutations effectuated by each cell in a time interval of Δt . For the optimal point, the average switching of the cells is around of 3 [kHz].

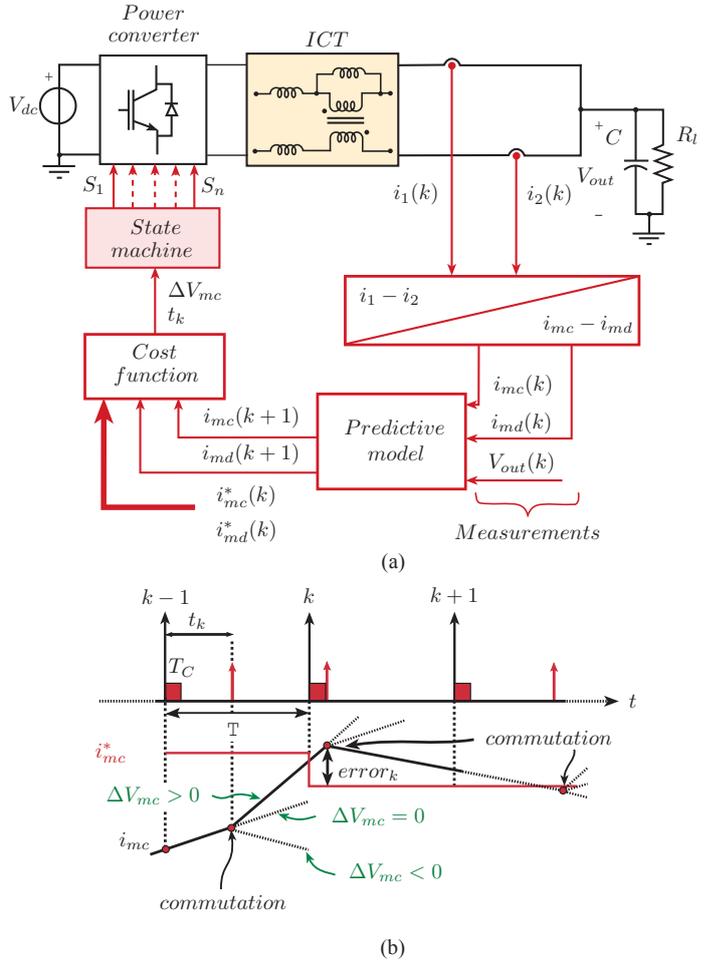


Fig. 6: (a) Control strategy with variable commutation instant (b) Commutations in the control strategy with variable commutation instant

V. CONTROL STRATEGY WITH VARIABLE COMMUTATION INSTANTS

Fig. 6 shows the different stages of this strategy. The first part uses a cost function containing the differences between the reference and the predicted values for the most important variables. This part allows the selection of the most suitable variation for the common mode voltage V_{mc} with an appropriated commutation instant. The second part uses a state machine for choosing the next state of the converter while the rest of variables are controlled. For two commutation cells connected in parallel, the cost function includes only the output current i_{mc} .

$$g = |i_{mc}^*(k+1) - i_{mc}(k+1)| \quad (6)$$

For simplicity, it is considered that the reference current i_{mc}^* does not change in one sampling interval, so $i_{mc}^*(k+1)$ is equal to $i_{mc}^*(k)$. The calculations of $i_{mc}(k+1)$ are based on the predictive model, the measures taken at each sampled time and the possible variation of the common mode voltage

V_{mc} . These variations are:

- $V_{mc} = +E/2$ if $S_x = 1$ with $x = 1, 2$.
- $V_{mc} = -E/2$ if $S_x = 0$ with $x = 1, 2$.
- $V_{mc} = 0$ if there is no commutation.

Another variant of the classical control strategy concerns the variable commutation instant, this is added to decrease the error of the controlled variable at the $(k+1)$ instant. The commutation instant and the predicted value of the output current are obtained from equations 1 and 2:

$$i_{mc}(t_k) = \frac{t_k}{L_{mc}}(V_{mc}(k) - V_{out}(k)) + i_{mc}(k) \quad (7)$$

Between $t_k \leq T_s$, the V_{mc} voltage may change ΔV_{mc} , so the current i_{mc} at $k+1$ is:

$$i_{mc}(k+1) = i_{mc}(t_k) + \frac{(T_s - t_k)}{L_{mc}} * V'_{mc} \quad (8)$$

where:

$$V'_{mc} = V_{mc}(k) - V_{out}(k) + \Delta V_{mc}(t_k)$$

$$t_k = \frac{T_s}{\Delta V_{mc}(t_k)} * V'_{mc} - \frac{L_{mc}}{\Delta V_{mc}(t_k)} * \epsilon_{i_{mc}}(k) \quad (9)$$

with:

$$\epsilon_{i_{mc}}(k) = |i_{mc}^*(k+1) - i_{mc}(k)| \quad (10)$$

The second part of the strategy is based in the selection of the next state, applying the desired output voltage and also controlling the differential current i_{md} . This selection is carried out with a state machine presented in Fig. 7. This state machine represents the different states of the studied topology. The 4 switches states are arranged and each row represents the same V_{mc} voltage level.

Depending of the actual state at k instant, two predicted values of $i_{mc}(k+1)$ and t_k are calculated corresponding to each possible ΔV_{mc} : $\Delta V_{mc} > 0$ and $\Delta V_{mc} = 0$ if the state at k is 0, $\Delta V_{mc} > 0$ and $\Delta V_{mc} < 0$ if the state is 1 or 2 and $\Delta V_{mc} < 0$ and $\Delta V_{mc} = 0$ if the state is 3.

The t_k and the ΔV_{mc} that minimizes the error are then chosen. The possible transitions between certain states are limited by the number of commutations. Therefore, only one commutation of a commutation cell for each calculation period T_s will be respected.

A. Control of the differential current i_{md}

The differential current is controlled by the time in the state that increases or reduces this current. If the ΔV_{mc} selected involves passing by the states 1 or 2, the state selected will be the one that takes the differential current closest to zero at the

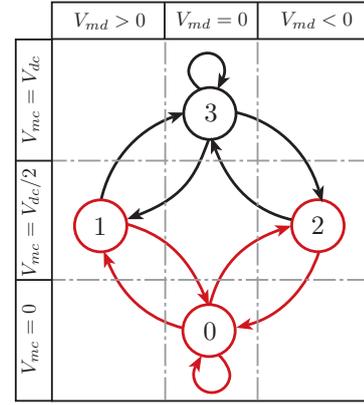


Fig. 7: State machine for two commutation cells connected in parallel.

end of the sampling time (that means that the reference value for the differential current is $i_{md}^* = 0$), anyway the algorithm does not stay in the states 1 and 2 for more than a sampling period T_s .

The control of the differential current is necessary due to the saturation of the magnetic core used in the ICT. During the transients, the value of this current can reach significant values and exceeds the established limits. A prediction of $i_{md}(k+1)$ and some strategies such as a reduction of the commutation instant t_k or the execution of a double commutation (two cells commute at the same time) can be used.

A general comparison between the two control strategies can be made. First, both methods use the prediction of i_{mc} and i_{md} in order to choose the optimal state to commute. The second strategy also requires some additional calculations such as the commutation instant t_k and the use of a state machine. However, for a power converter structure with a higher number of states, the second strategy can simplify the number of calculations to do. The predictions of i_{mc} are carried out with the possible variation of the common voltage ΔV_{mc} and not with each state of the converter.

On the other hand, the implementation of the classical MPC strategy is easier than the strategy using variable commutation instants but its optimal operation is limited to the operational point where the weighting coefficients were calculated. An important advantage of the second strategy concerns its ability to work optimally in different operational points. This strategy can also be used with more complex converters, using the serial and the parallel connection of commutation cells [12]. The main drawback of this strategy appears when t_k is less than T_C and a higher ripple can be produced in the output current, a solution taking into account this time delay can also be used [13].

VI. EXPERIMENTAL RESULTS

The parameters used for obtaining the optimal point are : $i_{mc}^* = 1.5 \pm 0.5$ [A], $V_{dc} = 25$ [V], $L_f = 6$ [mH], $L_m = 0$ [mH], $C = 470$ [μ F], $R_{1,2} = 250$ [m Ω], $R_l = 7$ [Ω], $f_s = 20$ [kHz]. These parameters are used in the experimental results presented in Fig. 8 and Fig. 9. The next table shows the total mean value of the absolute difference between the references and the measurements for the common and differential current when the structure is working in the optimal point. For the proposed strategy, the mean values of \bar{e}_{mc} and \bar{e}_{md} are lower than the MPC strategy and the mean switching frequency is the highest possible.

Fig. 8 and Fig. 9 shows the results for a squared variation in the output current reference. For some operational points in the proposed strategy, the ripple of i_{md} is higher than the ripple obtained with the MPC strategy. This is because the differential current in the proposed strategy is controlled in a secondary place by a state machine whereas for the MPC, this current is controlled directly in the cost function.

TABLE II: Comparison between the two control strategies

Parameter	MPC strategy	Control strategy proposed
\bar{e}_{mc}	0.050 [A]	0.025 [A]
\bar{e}_{md}	0.057 [A]	0.0413 [A]
\bar{f}_{comm}	4.56 [kHz]	5 [kHz]
THD	0.13%	0.08%

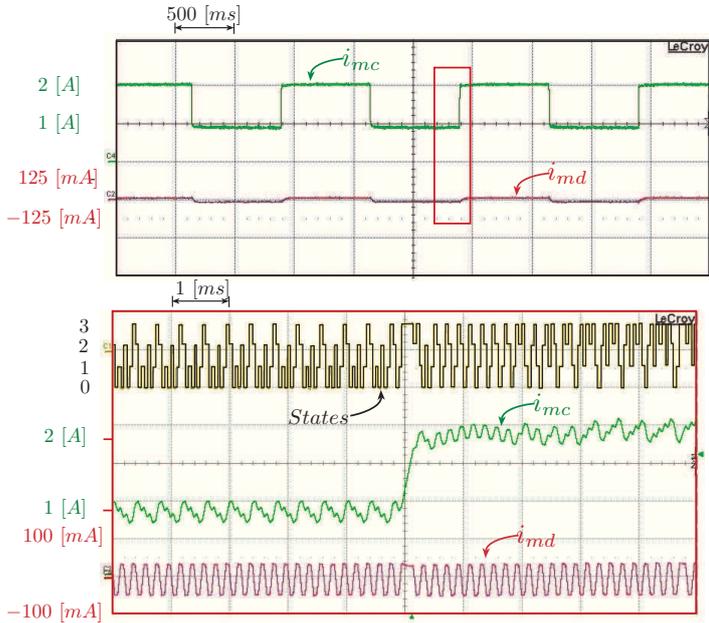


Fig. 8: Response of the MPC strategy for a squared current reference

Fig. 10 and Fig. 11 are obtained when a sinusoidal current $i_{mc}^* = 1 + 0.5 \sin(40\pi * t)$ [A] is used as reference and the input voltage is $V_{dc} = 40$ [V]. Table II shows THD values of the output current for both control strategies. The output

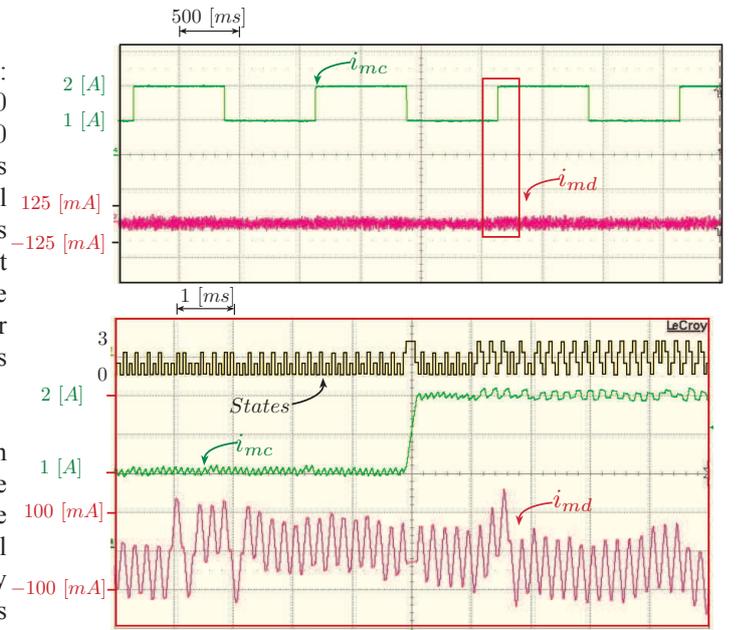


Fig. 9: Response of the strategy with variable commutation instants for a squared current reference

current obtained with the strategy using variable commutations instants has better quality.

In order to compare the two strategies, the sampling frequency used in the experimental results was $f_s = 20$ [kHz]. The classical MPC strategy has a better performance with higher frequencies, this is because the commutation instants are fixed and the variation of the controlled variables decreases with the sampling time. The second strategy, using variable commutation instants, is a good solution when low sampled frequencies will be used using the main advantages of the MPC (selection of an optimal state, fast dynamic response).

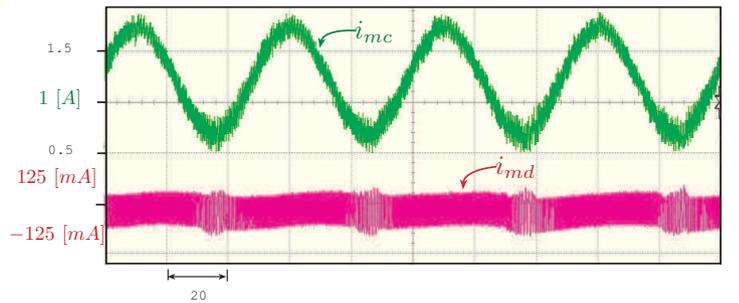


Fig. 10: Response of the MPC strategy for a sinusoidal current reference

VII. CONCLUSION

This paper presents the application of two control strategies with two commutations cells connected in parallel. This connection allows higher output currents with the classical

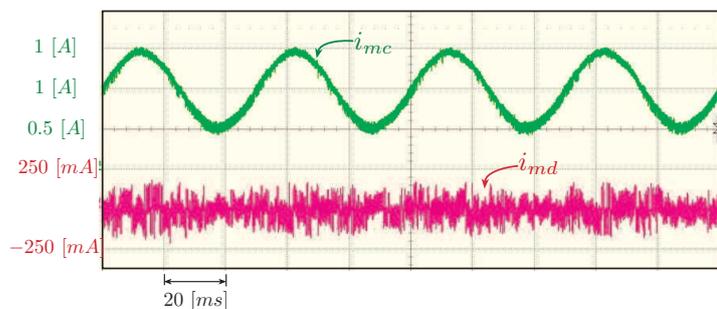


Fig. 11: Response of the strategy with variable commutation instants for a sinusoidal current reference

semiconductor technology. In order to keep a good behavior of the structure, the differential current has to be controlled. Thus, the studied strategies have to be able to control the output current maintaining the differential current around zero.

The first strategy is the classical Model Predictive Control (MPC) that uses the mathematical model of the system and a cost function for selecting the optimal state of the converter at each sampling instant. The calculation of the weighting coefficients employed in the cost function is carried out for a specific operational point.

The second strategy based in MPC with variable commutation instants is also presented. This strategy reduces the selection of an adequate cost function when several variables have to be controlled. The first part of the strategy includes the calculation of different commutation instants and the prediction of the output current for all the possible ΔV_{mc} . The second part of the algorithm uses a simplified cost function including only the variable to be controlled (i_{mc}) in order to select the optimal voltage to apply. The last part of the algorithm uses a state machine for controlling the states of the converter and also the others variables, such as the differential current i_{md} .

Experimental results are presented for a steady state response

and also for squared and sinusoidal variations of the current reference. The results obtained with the proposed strategy have better characteristics than the results obtained with the classical MPC.

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