IEEE PEDS 2017, Honolulu, USA
12 – 15 December 2017

Indirect Model Predictive Control Strategies for a Direct Matrix Converter with Mitigation of Input Filter Resonances

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***Abstract*—The direct matrix converter has twenty-seven available switching states. This implies that the implementation of predictive control techniques in this converter requires high computational cost while an adequate selection of weighting factors in order to control both input and output sides. In addition, the technique presents a variable switching frequency which could produce resonances in the input filter damaging the performance of the system. In this paper, two indirect model predictive current control strategies are proposed in order to simplify the computational cost while avoiding the use of weighting factors. The first method consists in a predictive current control strategy with minimization of the reactive power minimization enhanced with an active damping implementation which allows mitigate resonances in the input side. The second proposal consist in an indirect model predictive current control with imposed sinusoidal source currents in the input side. Simulated results confirm the feasibility of the proposals demonstrating that with both alternatives it is possible to mitigate the resonances on the input filter.**

***Index Terms*—active damping, current control, matrix converters, predictive control, finite control set model predictive control, fictitious dc-link.**

NOMENCLATURE

$\mathbf{i_s}$	Source current	$[i_{sA}\ i_{sB}\ i_{sC}]^T$
$\mathbf{v_s}$	Source voltage	$[v_{sA}\ v_{sB}\ v_{sC}]^T$
$\mathbf{i_i}$	Input current	$[i_A\ i_B\ i_C]^T$
$\mathbf{v_i}$	Input voltage	$[v_A\ v_B\ v_C]^T$
i_{dc}	Fictitious dc-link current	
v_{dc}	Fictitious dc-link voltage	
$\mathbf{i_o}$	Load current	$[i_a\ i_b\ i_c]^T$
$\mathbf{v_o}$	Load voltage	$[v_a\ v_b\ v_c]^T$
$\mathbf{i}^*$	Load current reference	$[i_a^*\ i_b^*\ i_c^*]^T$
C_f	Input filter capacitor	
L_f	Input filter inductor	
R_f	Input filter resistor	
R	Load resistance	
L	Load inductance	

I. INTRODUCTION

In comparison with the traditional back-to-back converter, the direct matrix converter (DMC) show some advantages in terms of power densities and capability to operate in harsh pressures and temperatures [1], [2]. This converter presents sinusoidal input and output currents as well as bidirectional power flow and adjustable input displacement power factor [2], [3]. Several modulation and control techniques have been implemented in this converter being the most popular Venturini, Pulse Width Modulation (PWM), Space Vector Modulation (SVM) as well as Direct Torque Control (DTC) and Model Predictive Control (MPC) [3]. Among them, MPC has called the attention in the last years and now this control technique is considered as a real alternative for the control of power converters [4]. MPC uses the mathematical model of the system to predict for each valid switching state of the converter the performance of the variables to be controlled at every sampling time. These predictions are compared with a given reference in a cost function and, the switching state that generates the minimal error between the prediction and the reference, is the one selected to be applied in the next sampling instant. Latest contributions have been focused in applications such as multilevel converters [5], [6], permanent magnet machines [7], shunt active power filters [8], PWM rectifiers [9], matrix converters [10]–[12], among others.

Despite the several progress of MPC for power converters, there are still some issues that are considered as an open topic for research such as computational cost, the weighting factor selection and the input filter resonance due to the variable switching frequency. As in the classical MPC only one vector is chosen in one sampling instant, the controlled variables present high ripple due to variable switching frequency operation, specially when the average switching frequency is close to the resonance frequency of the input filter, affecting the performance of the system and damaging the waveforms of both input and source currents.

In order to solve these issues, in this paper is proposed an indirect model predictive current control strategy. The idea consists in to emulate the DMC as a two stage converter linked by a fictitious dc-link allowing a separated and parallel control of both input and output stages, avoiding the use of weighting factors. Two strategies are proposed here. In the first proposal, the method is enhanced with an active damping implementation which consists in to emulate a damping resistor in parallel to the capacitor of the input filter. The second strategy proposes an indirect model predictive control with imposed sinusoidal source currents at the input side.

II. Mathematical Model of the DMC

The DMC, shown in Fig. 1, is composed by bidirectional switches which directly connect the input side with the load side without including any intermediate dc-link storage device. Between the input ac source and bidirectional switches, a filter (normally LC filter) is connected to prevent over-voltage due to fast commutation of currents $\mathbf{i_i}$ and also to eliminate high-frequency harmonics in the input currents $\mathbf{i_s}$. For the safe operation of this converter, there are some operation constrains which are expressed by:

$$S_{Ay} + S_{By} + S_{Cy} = 1, \quad \forall\, y = a,\, b,\, c \tag{1}$$

In this equation it is possible to deduce that the current cannot be interrupted abruptly due to the inductive nature of the load, and the operation of the switches cannot short-circuit two input lines, owing to the presence of capacitors in the input filter. To obtain the mathematical model of the DMC, the input and output relationship of the converter is defined as:

$$\mathbf{v_o} = \mathbf{T}\ \mathbf{v_i} \tag{2}$$

$$\mathbf{i_i} = \mathbf{T}^T \mathbf{i_o} \tag{3}$$

with $\mathbf{T}$ the instantaneous transfer matrix which represent the switching states as:

$$\mathbf{T} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \tag{4}$$

These equations are the base for all modulation and control techniques for the DMC. Based on the idea proposed in [1], [13], some techniques use the concept of fictitious dc-link in order to simplify the modulation and control of the DMC. The idea separates the converter in a three-phase rectifier and a three-phase inverter linked by a fictitious dc-link such as represented in Fig. 2. Associated to the rectifier are six active current space vectors, represented in Fig. 3 (left) and Table I. The inverter have associated eight voltage space vectors which are represented in Fig. 3 (right) and Table II. The technique modulates both converters separately, but considering the relationship between both stages.

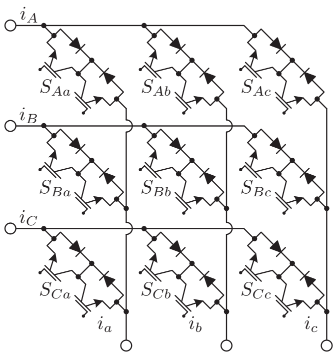

Fig. 1. Power circuit of the direct matrix converter.

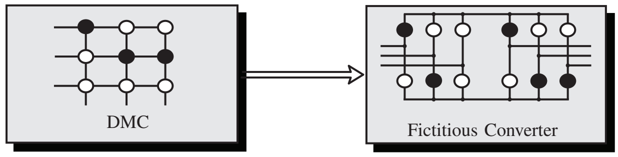

Fig. 2. Representation of the fictitious dc-link concept for the DMC.

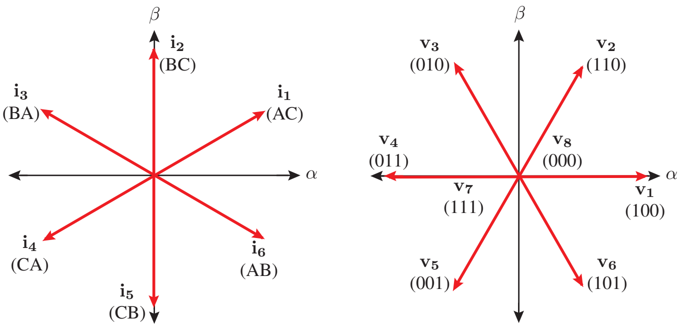

Fig. 3. Current and voltage space vector of the fictitious converter. Left: current space vectors for the fictitious rectifier, Right: voltage space vectors for the fictitious inverter.

TABLE I
Valid switching state on the fictitious rectifier

#	S_{r1}	S_{r2}	S_{r3}	S_{r4}	S_{r5}	S_{r6}	i_A	i_B	i_C	v_{dc}
1	1	1	0	0	0	0	i_{dc}	0	$-i_{dc}$	v_{AC}
2	0	1	1	0	0	0	0	i_{dc}	$-i_{dc}$	v_{BC}
3	0	0	1	1	0	0	$-i_{dc}$	i_{dc}	0	$-v_{AB}$
4	0	0	0	1	1	0	$-i_{dc}$	0	i_{dc}	$-v_{AC}$
5	0	0	0	0	1	1	0	$-i_{dc}$	i_{dc}	$-v_{BC}$
6	1	0	0	0	0	1	i_{dc}	$-i_{dc}$	0	v_{AB}

TABLE II
Valid switching state on the fictitious inverter

#	S_{i1}	S_{i2}	S_{i3}	S_{i4}	S_{i5}	S_{i6}	v_{ab}	v_{bc}	v_{ca}	i_{dc}
1	1	1	0	0	0	1	v_{dc}	0	$-v_{dc}$	i_a
2	1	1	1	0	0	0	0	v_{dc}	$-v_{dc}$	i_a+i_b
3	0	1	1	1	0	0	$-v_{dc}$	v_{dc}	0	i_b
4	0	0	1	1	1	0	$-v_{dc}$	0	v_{dc}	i_b+i_c
5	0	0	0	1	1	1	0	$-v_{dc}$	v_{dc}	i_c
6	1	0	0	0	1	1	v_{dc}	$-v_{dc}$	0	i_a+i_c
7	1	0	1	0	1	0	0	0	0	0
8	0	1	0	1	0	1	0	0	0	0

III. Indirect Model Predictive Control Method

In Fig. 4 is represented the general idea of the classical MPC for the DMC. In this control strategy, both input and output stages are controlled together by considering a predictive model of the instantaneous reactive input power and a predictive model of the load currents. These predictions are compared with their respective references in a single cost function (so it is necessary also to consider a weighting factor in order to provide more priority to one of the controlled variables). The cost function is evaluated for each of the twenty-seven available switching states of the DMC and, the switching state that minimizes this cost function, is the one selected to be applied to the converter in the next sampling instant. In this control method two main issues are observed. Firstly, selecting a suitable weighting factor correctly is significant

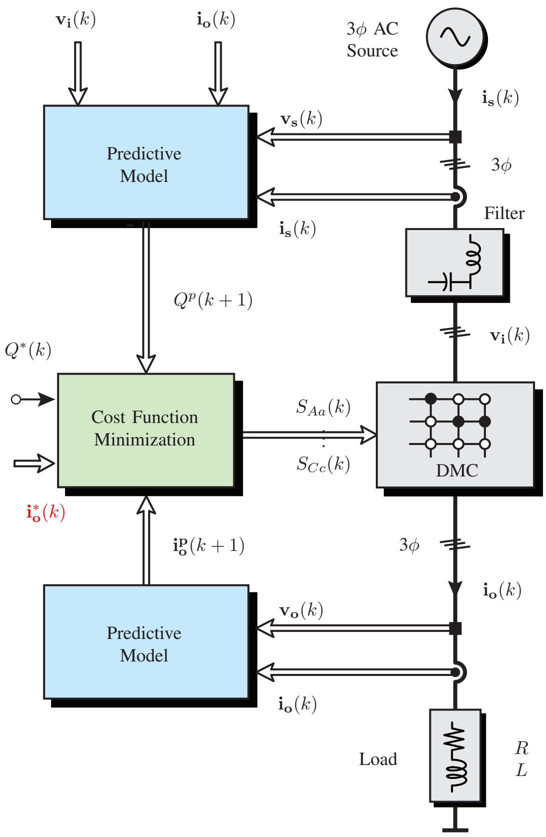

Fig. 4. Classic predictive current control strategy for the DMC.

in order to balance the control priority of load current and input reactive power. Secondly, as the full converter control is considered, a large amount of available switching states is employed, requiring a fast microcontroller for such amount of calculations. In order to solve these issues, in this paper we use the concept of fictitious dc-link in order to propose an indirect MPC for the DMC. The idea of this proposal is to separate the control of both input and output fictitious stages of the converter in order to avoid complex and large calculations and as well simplify the controller while avoiding the use of weighting factors.

A. *Control Strategy with Active Damping Implementation*

As in the classical MPC method for the DMC only one vector is selected to be applied in one sampling instant, the controlled variables present high ripple due to variable switching frequency operation, specially when the average switching frequency is close to the resonance frequency of the input filter, affecting the performance of the system and damaging the waveforms of both input and source currents. In this part of the paper is proposed the implementation of an active damping method in order to mitigate resonances in the input filter. This implementation is done on the load side of the converter by modifying the load current reference but this modification is based on the measurement of the capacitor voltage in the input side [14], [15].

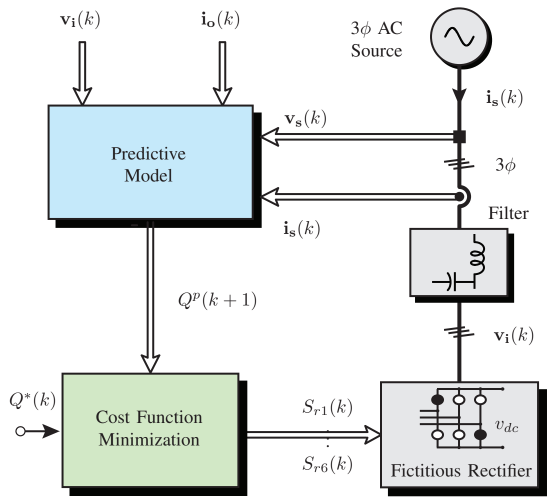

Fig. 5. Indirect predictive control strategy for the fictitious rectifier.

1) Control of the Rectifier: The proposed technique is detailed in Fig. 5, where the minimization of the instantaneous reactive power is considered. It consists in to control the input side of the converter by using the available switching states indicated in Fig. 3 (left) and Table I, and considering the mathematical relationship between input and output voltages and currents, defined as:

$$v_{dc} = \begin{bmatrix} S_{r1} - S_{r4} & S_{r3} - S_{r6} & S_{r5} - S_{r2} \end{bmatrix} \mathbf{v_i} \qquad (5)$$

$$\mathbf{i_i} = \begin{bmatrix} S_{r1} - S_{r4} \\ S_{r3} - S_{r6} \\ S_{r5} - S_{r2} \end{bmatrix} i_{dc} \qquad (6)$$

Such as in the classical MPC for the DMC, in the control of the input side it is necessary the prediction model of the source current which is given by:

$$\frac{d\mathbf{i_s}}{dt} = \frac{1}{L_f}(\mathbf{v_s} - \mathbf{v_i}) - \frac{R_f}{L_f}\mathbf{i_s} \qquad (7)$$

$$\frac{d\mathbf{v_i}}{dt} = \frac{1}{C_f}(\mathbf{i_s} - \mathbf{i_i}) \qquad (8)$$

Because the predictive controller is formulated in discrete time, it is necessary to derive a discrete time model for the system. By considering the guidelines presented in [16] for the current and voltage predictions, it is possible to define the cost function g_r associated to the input control in the α-β plane:

$$g_r = [v_{s\alpha}(k+1)i_{s\beta}(k+1) - v_{s\beta}(k+1)i_{s\alpha}(k+1)]^2 \qquad (9)$$

2) Control of the Inverter: The control diagram of this stage is represented in Fig. 6. In order to enhance the performance of the system and to mitigate the potential resonance of the input filter, the predictive controller is combined with an active damping method, by modifying the load current reference such as shown in Fig. 7 and detailed in [14], [15]. With this is not necessary any additional measurements or any modification to the predictive controller, being easy to implement.

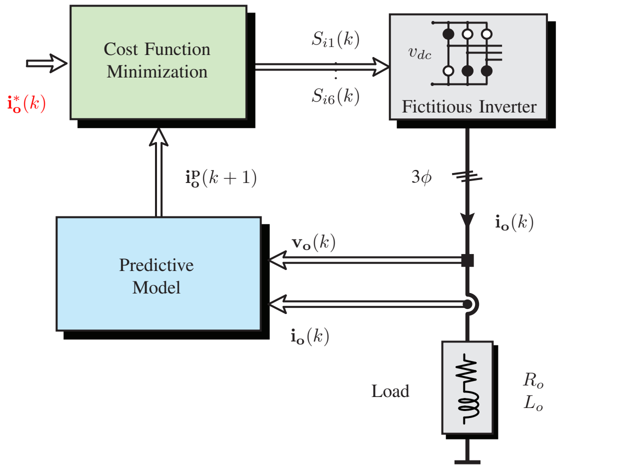

Fig. 6. Indirect predictive control strategy for the fictitious inverter.

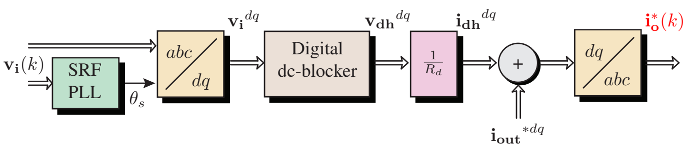

Fig. 7. Active damping implementation.

This control method achieves the attenuation of system resonance without affecting the efficiency of the converter, because a virtual harmonic resistive damper R_d is considered, which is immune to system parameter variations, in parallel with the input filter capacitors C_f, to reduce the system harmonics without affecting the fundamental component. The converter draws a damping current proportional to the capacitor voltage, which is extracted by the converter itself, emulating the damping resistance R_d as indicated by:

$$i_d = \frac{\mathbf{v_i}}{R_d} \tag{10}$$

The mathematical model of the inverter and load is defined as:

$$i_{dc} = \begin{bmatrix} S_{i1} & S_{i3} & S_{i5} \end{bmatrix} \mathbf{i} \tag{11}$$

$$\mathbf{v_o} = \begin{bmatrix} S_{i1} - S_{i4} \\ S_{i3} - S_{i6} \\ S_{i5} - S_{i2} \end{bmatrix} v_{dc} \tag{12}$$

$$\mathbf{v_o} = L\frac{d\mathbf{i_o}}{dt} + R\mathbf{i_o} \tag{13}$$

With these definitions, a forward Euler approximation is used to define the prediction model of the output side as:

$$\mathbf{i_o}(k+1) = c_1\mathbf{v_o}(k) + c_2\mathbf{i_o}(k) \tag{14}$$

where, $c_1 = T_s/L$ and $c_2 = 1 - RT_s/L$, are constants dependent on load parameters and the sampling time T_s.

Finally, the associated cost function g_i for the output stage in α-β plane is defined as:

$$g_i = (i_\alpha^* - i_\alpha(k+1))^2 + (i_\beta^* - i_\beta(k+1))^2 \tag{15}$$

where in this case the load current reference is given by the implementation shown in Fig. 7.

B. *Control Strategy with Imposed Sinusoidal Source Currents*

The second control strategy proposed in this paper consider the same block diagrams of the previous presented method but in this case, the control of the input side is modified imposing a sinusoidal source current instance the minimization of the instantaneous reactive power. In this case, the associated cost function to the input side control is given by:

$$g_r = (i_{s\alpha}^* - i_{s\alpha}(k+1))^2 + (i_{s\beta}^2 - i_{s\beta}(k+1))^2) \tag{16}$$

where the source current reference of the DMC, is obtained based on the apparent power expression on the input side. For a deeply detail of the generation of this reference please refer to [17]. On the load side this control scheme is exactly the same as the first proposal but in this case there is not any active damping implementation so the controller assumes that $\mathbf{i_{dh}}^{dq} = 0$.

C. *Relationship between the fictitious converter and the DMC*

As the control is done for each fictitious converter, the chosen switching states by the predictive controller need to be adapted to the valid switching states of the DMC. As established in eq. (2), the relationship between the input voltage $\mathbf{v_i}$ and load voltage $\mathbf{v_o}$ is depending on the state of the switching given by matrix $\mathbf{T}$. Based on the fictitious definition, the load voltage $\mathbf{v}$ is given as indicated in eq. (12). At the same time, the fictitious dc-link voltage v_{dc} is given by eq. (5). In summary,

$$\mathbf{v_o} = \begin{bmatrix} S_{i1} - S_{i4} \\ S_{i3} - S_{i6} \\ S_{i5} - S_{i2} \end{bmatrix} \begin{bmatrix} S_{r1} - S_{r4} & S_{r3} - S_{r6} & S_{r5} - S_{r2} \end{bmatrix} \mathbf{v_i} \tag{17}$$

and thus the relationship between the switches of the DMC and fictitious converter is given as:

$$\begin{bmatrix} S_{Aa} \\ S_{Ba} \\ S_{Ca} \\ S_{Ab} \\ S_{Bb} \\ S_{Cb} \\ S_{Ac} \\ S_{Bc} \\ S_{Cc} \end{bmatrix} = \begin{bmatrix} (S_{i1} - S_{i4})(S_{r1} - S_{r4}) \\ (S_{i1} - S_{i4})(S_{r3} - S_{r6}) \\ (S_{i1} - S_{i4})(S_{r5} - S_{r2}) \\ (S_{i3} - S_{i6})(S_{r1} - S_{r4}) \\ (S_{i3} - S_{i6})(S_{r3} - S_{r6}) \\ (S_{i3} - S_{i6})(S_{r5} - S_{r2}) \\ (S_{i5} - S_{i2})(S_{r1} - S_{r4}) \\ (S_{i5} - S_{i2})(S_{r3} - S_{r6}) \\ (S_{i5} - S_{i2})(S_{r5} - S_{r2}) \end{bmatrix} \tag{18}$$

IV. Results

In order to validate the effectiveness of the proposed method, simulation results in Matlab-Simulink were carried out for both proposals, the first with instantaneous input reactive power minimization and active damping implementation and the second with imposed sinusoidal source currents. The simulation parameters are shown in Table III.

Fig. 8 and Fig. 9 show simulations results for the proposed indirect predictive controller with instantaneous reactive power

TABLE III
PARAMETERS OF THE IMPLEMENTATION

Variables	Description	Value
V_s	Amplitude ac-voltage	311 [V]
C_f	Input filter capacitor	21 [μF]
L_f	Input filter inductor	400 [μH]
R_f	Input filter resistor	0.5 [Ω]
R	Load resistance	10 [Ω]
L	Load inductor	10 [mH]
T_s	Sampling time	20 [μs]
	Simulation step	1 [μs]

minimization. Before $t = 0.06$[s], the control strategy is evaluated without the active damping implementation.

After $t = 0.06$[s], the control strategy is evaluated with the implementation of the active damping technique. In Fig. 8(a) is observed a source current i_{sA} in phase with to its respective source voltage v_{sA} but before the implementation of the active damping method, this current is highly distorted with a THD of 14.30%. After the implementation of the active damping method, the source current is improved obtaining almost a sinusoidal waveform with a THD of 4.17%. The effect and performance of the input filter is also reflected in this figure where the high order harmonics present in Fig. 8(b) are eliminated as expected. The effect of the input filter resonance is also evident in the capacitor voltage waveform v_A, where before $t = 0.06$[s] presents also an oscillation but it is improved with the implementation of the active damping method. In Fig. 8(b) it can be observed the commutated input current i_A, which is given as function of the DMC switches and the load currents $\mathbf{i_o}$. A very good tracking of the load currents $\mathbf{i_o}$ to its respective references $\mathbf{i_o^*}$ is observed in Fig. 9(a) with a sinusoidal waveform and a THD of 0.57% and 0.84% before and after the implementation of the active damping strategy, respectively. In this case the reference is established as I_o^*=16[A]@30Hz. In Fig. 9(b) is also observed the load voltage which is given as a function of the DMC switches and the input voltages $\mathbf{v_i}$. Fig. 10 and Fig. 11 show simulations results for the proposed indirect predictive controller with imposed sinusoidal source currents in the input side. In this case, there is not active damping implementation and thus during all the simulation time only one case is evaluated. As it can be seen in Fig. 10(a) a sinusoidal source current waveform i_{sA} is obtained tracking very well its respective source current reference i_{sA}^* with a THD of 2.37%. It is evident in both Fig. 10(a) and Fig. 10(b) that the resonance of the input filter is totally mitigated just by imposing a sinusoidal waveform in the input side, drastically improving the performance of the system. Similarly to the previous case, the output currents $\mathbf{i_o}$ present a very good tracking of their respective references $\mathbf{i_o^*}$ with a THD of 0.99%. By considering this proposal, better results than those obtained with the active damping implementation are obtained.

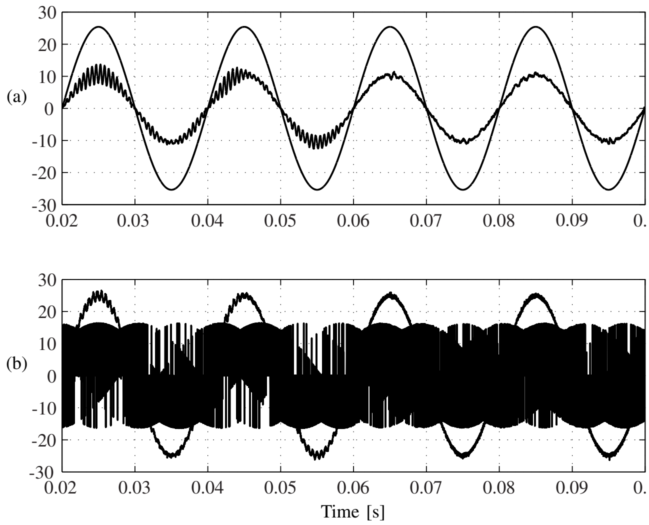

Fig. 8. Simulation results of the proposed indirect predictive control method with instantaneous reactive power minimization. Before $t = 0.06$ [s] without active damping, after $t = 0.06$ [s] with active damping implementation: (a) source voltage v_{sA} [V/10] and source current i_{sA} [A]; (b) capacitor voltage v_A [V/10] and input current i_A [A].

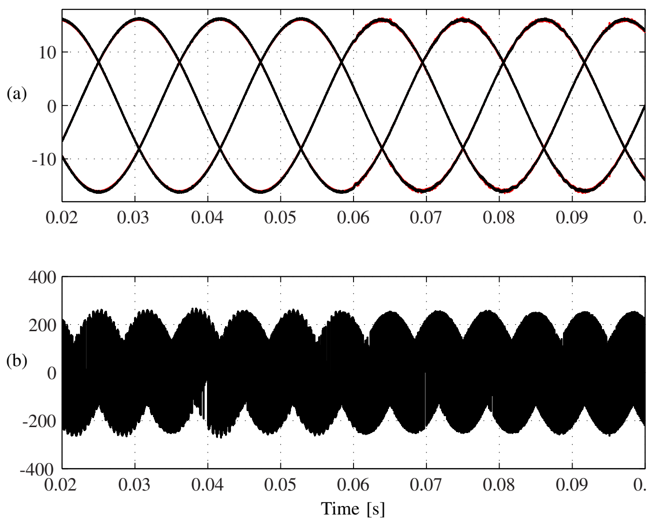

Fig. 9. Simulation results of the proposed indirect predictive control method with instantaneous reactive power minimization. Before $t = 0.06$ [s] without active damping, after $t = 0.06$ [s] with active damping implementation: (a) load currents $\mathbf{i_o}$ [A] and its references $\mathbf{i_o}^*$ [A]; (b) load voltage v_a [V].

V. CONCLUSION

In this paper have been presented two indirect model predictive current control strategies for the DMC. The first method consists on an indirect predictive control strategy with minimization of the instantaneous reactive input power which has been enhanced with an active damping implementation. The second method consists in an imposed sinusoidal source currents in the input side. Both methods use the idea of fictitious dc-link in order to separate the control of both input and output stages of the converter. By doing this, it is possible to reduce the complexity of the control, but also avoid the calculation of a suitable weighting factor for the control of both instantaneous reactive input power and load currents variables. At the same time, with the active damping implementation, it

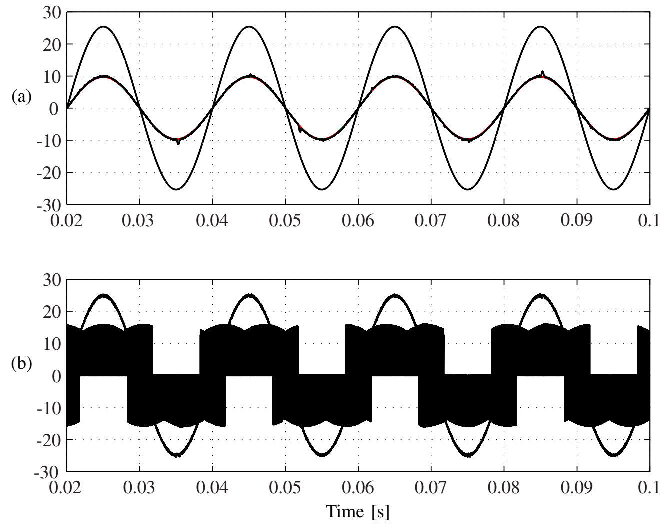

Fig. 10. Simulation results of the proposed indirect predictive control method with imposed sinusoidal source currents: (a) source voltage v_{sA} [V/10], source current reference i_{sA}^{*} [A] and source current i_{sA} [A]; (b) capacitor voltage v_A [V/10] and input current i_A [A].

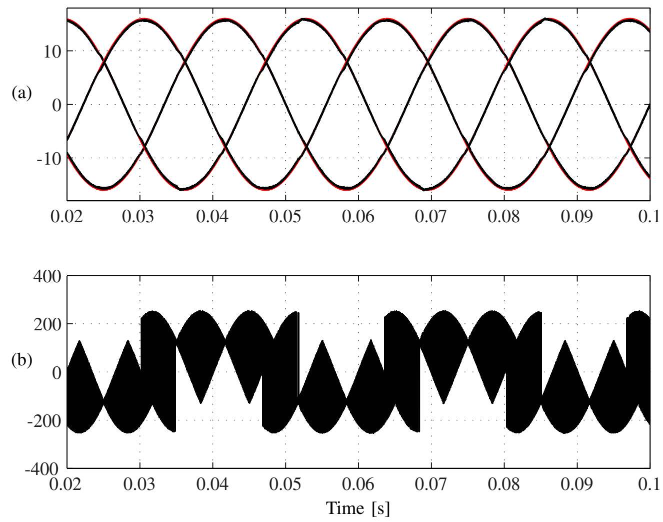

Fig. 11. Simulation results of the proposed indirect predictive control method with imposed sinusoidal source currents: (a) load currents $\mathbf{i_o}$ [A] and its references $\mathbf{i_o}^*$ [A]; (b) load voltage v_a [V].

is possible to mitigate the resonances of the input filter in both input currents and input voltages, improving the performance of the full system. But by imposing a sinusoidal source current it is possible to obtain a better performance of the system. By considering the proposed strategies, a new alternative has emerged for the control of both the input and load currents in a direct matrix converter.

Acknowledgments

The authors would like to thank the financial support of Programa en Energías CONICYT - Ministerio de Energía ENER20160014 and FONDECYT Regular 1160690 Research Project.

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