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Indirect Model Predictive Control Strategies with Input Filter Resonance Mitigation for a Matrix Converter Operating at Fixed Switching Frequency

M. Rivera
Faculty of Engineering
Universidad de Talca, Curicó, Chile
marcoriv@utalca.cl

A. Nikolic
Electrical Engineering Institute
Nikola Tesla, Belgrade, Serbia
anikolic@ieent.org

L. Tarisciotti, P. Wheeler
Dep. of Electrical and Electronic Engineering
University of Nottingham, Nottingham, UK
pat.wheeler@nottingham.ac.uk

***Abstract*—The main issues of the implementation of model predictive control in a direct matrix converter are the high computational cost, the adequate selection of weighting factors and the variable switching frequency which could produce resonances in the input filter. In order to solve these problems, in this paper are proposed two indirect model predictive control techniques with input filter resonance mitigation operating at fixed switching frequency. The method is based on the fictitious dc-link concept, which has been used in the past for the classical modulation and control techniques of the direct matrix converter. Simulated results confirm the feasibility of the proposal demonstrating that it is an alternative to classical predictive control strategies for the direct matrix converter.**

***Index Terms*—active damping, current control, matrix converters, indirect 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

The direct matrix converter (DMC) is an ac-ac power conversion topology that directly connects the input with the output without the necessity of any storage element. This converter accomplish all the desired characteristics of an ideal converter such as sinusoidal input and output currents as well as bidirectional power flow and adjustable input displacement power factor [1].

Among several modulation and control strategies, Model Predictive Control (MPC) has been presented as a real alternative to simplify the control of the DMC [1], [2].

The technique 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. Despite the several progress of MPC, there are still some issues considered as an open topic for research. One of these issues is the correct selection of weighting factors when there are several control objectives. This issue is very relevant because it has a significant effect on the system performance. In most of the cases, this selection is done by using empirical process but there are some papers that offer some guidelines for the optimal weighting factor selection [3]–[6] nevertheless, most of them are complex solutions and require high computation cost. Another issue of MPC is 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 which could also produce resonances in the input filter, affecting the performance of the system. One of the most popular techniques to solve this problem has been modulated MPC (M2PC) where the cost function is used for the optimal selection of adjacent vectors and duty cycles in one sampling instant to apply them to the converter in the next period. The idea is to emulate SVM by using MPC [7], [8]. By doing this, the control strategy keeps the advantages of traditional MPC techniques such as fast dynamic response, multi objective control, easy inclusion of nonlinearities and constrains but ensuring a fixed switching operation, reducing the ripple of the controlled variables and improving the performance of the system. But the problem of applying this idea in matrix converters is that it requires high computational cost because the twenty-seven predictions are calculated twice every sampling instant. To solve the issues for the MPC in the DMC such as computational cost, weighting factor selections and the operation at variable switching frequency, the contribution of this paper is to propose two indirect model predictive current control strategies working at fixed switching frequency in order to also mitigate resonances on the input filter.

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 and choosing into the cost function a set of optimal vectors and their respective duty cycles to be applied to the converter by using a predefined switching pattern.

II. Mathematical Model of the DMC

As shown in Fig. 1, the DMC is composed by nine bidirectional switches which directly connect the input side with the load side without including any dc-link storage device. Between the ac source and bidirectional switches, an input filter is connected to prevent over-voltage due to fast commutation of currents $\mathbf{i_i}$ and to eliminate high-frequency harmonics in the input currents $\mathbf{i_s}$. Due to the inductive nature of the load, the current cannot be interrupted abruptly, and the operation of the switches cannot short-circuit two input lines, owing to the presence of capacitors in the input filter. These restrictions can be expressed by:

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

The relations between the input and output variables of the DMC are defined by:

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

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

where $\mathbf{T}$ is the instantaneous transfer matrix defined as:

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

There are some techniques that uses the concept of fictitious dc-link in order to simplify the modulation and control of the DMC. The method consist in to divide the converter in a current source rectifier and a voltage source inverter linked by a fictitious dc-link such as represented in Fig. 2 [9], [10].

The rectifier have associated six active current space vectors which are represented in Fig. 3 (left), which are also represented in 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. This allows, for instance, that one stage of the converter can be controlled by one modulation or control technique and the other stage by another which could be different.

III. Indirect Model Predictive Control Methods for the DMC with Fixed Switching Frequency

In [11] is presented a M2PC technique for a DMC feeding an induction machine where 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.

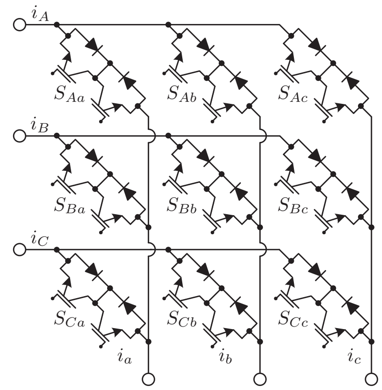

Fig. 1. Power circuit of the direct matrix converter.

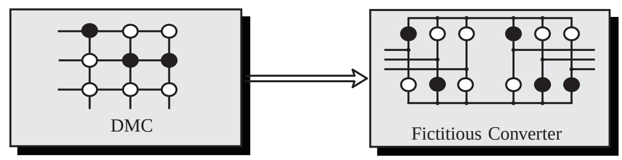

Fig. 2. Representation of the fictitious dc-link concept for the DMC.

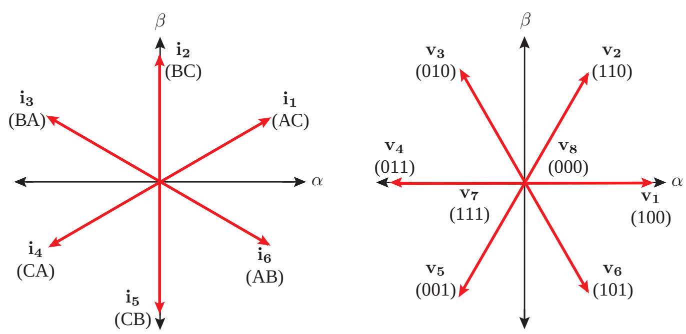

Fig. 3. Current and voltage space vectors of the fictitious converter. Left: current space vectors for the fictitious rectifier, right: voltage space vectors for the fictitious inverter.

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

At every sampling instant is chosen three active and three zero optimal vectors which are applied to the converter. In the method shown in [11] two main issues are observed: first, it is necessary the correct selection of a suitable weighting factor value in order to prioritise for the control of the load current or the instantaneous reactive input power, and second, as the full converter control is considered, a large amount of available switching states should be computed.

In order to solve these issues, in this paper we use the concept of fictitious dc-link in order to propose an indirect model predictive control 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 of the Rectifier

The mathematical model of the rectifier stage is shown in equations (5) and (6), respectively:

$$v_{dc} = \left[\begin{array}{ccc} S_{r1}-S_{r4} & S_{r3}-S_{r6} & S_{r5}-S_{r2} \end{array} \right] \mathbf{v_i} \tag{5}$$

$$\mathbf{i_i} = \left[\begin{array}{c} S_{r1}-S_{r4} \\ S_{r3}-S_{r6} \\ S_{r5}-S_{r2} \end{array} \right] i_{dc} \tag{6}$$

As indicated in Fig. 3 (left) and Table I, there are six active current space vectors which correspond to the suitable switching states of the rectifier. The proposed technique detailed in Fig. 4, consists in to control the input side of the converter by considering these available switching states and considering the mathematical relationship between input and output voltages and currents. Similarly to the classical predictive strategy in the DMC, for the control of the input side it is necessary the prediction model of the source current which is given by the following relations:

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

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

In this paper two strategies are presented for the input side. The first method consists in a minimization of the instantaneous reactive power which is represented by the following cost function:

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

The second method consists in to impose a sinusoidal waveform in the source current which is reflected as follows:

$$g_r \;=\; [i^*_{s\alpha} - i_{s\alpha}(k+1)]^2 + [i^*_{s\beta} - i_{s\beta}(k+1)]^2 \tag{10}$$

For both methods, the predictive controller is formulated in discrete time and thus it is necessary to derive a discrete time model of the system by considering the guidelines presented in [12] for the current and voltage predictions. At every sampling instant T_s, each pair of current vectors are evaluated

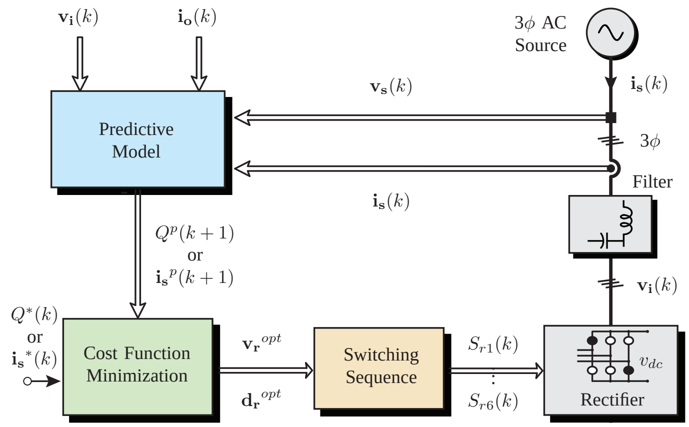

Fig. 4. Indirect predictive control strategy for the fictitious rectifier.

for cost function g_r which means that for each sector two cost functions are given, the first associated to one current vector g_{r1} and other related to the adjacent current vector g_{r2}. Later, these cost functions are used to compute the duty cycles which are calculated assuming that they are proportional to the inverse of the corresponding cost function value, where K_r is a constant to be determined:

$$\begin{aligned} d_{r1} &= K_r/g_{r1} \\ d_{r2} &= K_r/g_{r2} \\ d_{r1}+d_{r2} &= 1 \end{aligned} \tag{11}$$

With these duty cycles and cost function values, is defined a new cost function which is given by

$$g_{rec} \;=\; d_{r1}g_{r1} + d_{r2}g_{r2} \tag{12}$$

This is done every sampling time for each of the six sectors. Finally, the pair of vectors that minimizes the cost function g_{rec} are selected as the optimal $\mathbf{v_r}^{opt}$ to be applied in the next period. The time that each vector is applied is given by:

$$\begin{aligned} t_{r1} &= d_{r1}T_s \\ t_{r2} &= d_{r2}T_s \end{aligned} \tag{13}$$

B. Control of the Inverter

The control diagram of this stage is represented in Fig. 5. The mathematical model of the inverter is defined as:

$$i_{dc} = \left[\begin{array}{ccc} S_{i1} & S_{i3} & S_{i5} \end{array} \right] \mathbf{i_o} \tag{14}$$

$$\mathbf{v_o} = \left[\begin{array}{c} S_{i1}-S_{i4} \\ S_{i3}-S_{i6} \\ S_{i5}-S_{i2} \end{array} \right] v_{dc} \tag{15}$$

The mathematical model of the load, assuming a passive RL load, is defined as:

$$\mathbf{v_o} = L\frac{d\mathbf{i_o}}{dt} + R\mathbf{i_o} \tag{16}$$

With these definitions, it is possible to define the prediction model of the output side using a forward Euler approximation in eq. (16), such as:

$$\mathbf{i_o}(k+1) = c_1\mathbf{v_o}(k) + c_2\mathbf{i_o}(k) \tag{17}$$

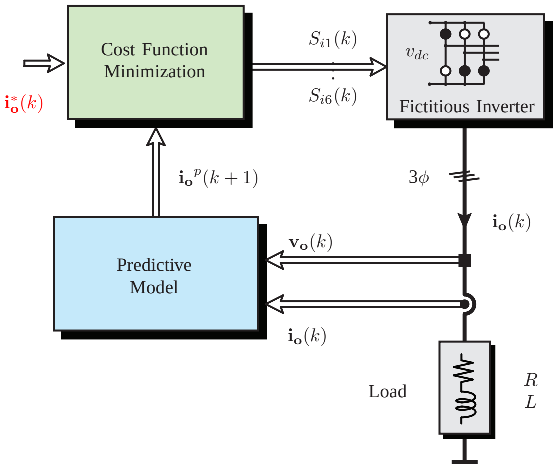

Fig. 5. Indirect predictive control strategy for the fictitious inverter.

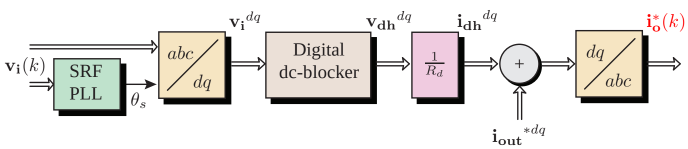

Fig. 6. Active damping implementation.

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. The associated cost function g_i is defined as:

$$g_i = [i_\alpha^* - i_\alpha(k+1)]^2 + [i_\beta^* - i_\beta(k+1)]^2 \tag{18}$$

In order to enhance the performance of the system and to mitigate the potential resonance of the input filter excited by potential harmonics in the ac source and the converter itself, in this paper we add an active damping technique to the predictive controller with instantaneous reactive power minimization, by modifying the load current reference as shown in Fig. 6 and indicated in [13], [14]. In this method, we use a virtual harmonic resistive damper R_d, which is immune to system parameter variations, in parallel with the input filter capacitors C_f, to suppress 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:

$$i_d = \frac{\mathbf{v_i}}{R_d} \tag{19}$$

This method is easy to implement, do not affects the efficiency of the converter and do not involves additional measurements or any modification to the predictive algorithm. For the method with imposed sinusoidal source currents, it is not necessary the implementation of active damping and thus in this case it is assumed that $\mathbf{i_{dh}}^{dq} = 0$. At every sampling instant T_s, each pair of voltage vectors and one zero vector are evaluated for cost function g_i which means that for each sector three cost functions are given g_{i0}, g_{i1} and g_{i2}.

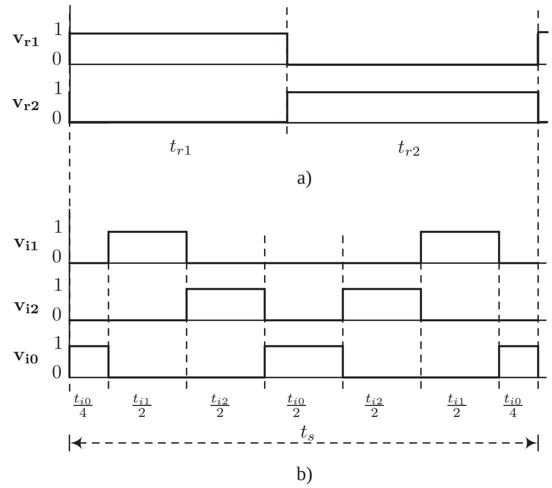

Fig. 7. Switching pattern: a) for the rectifier side; b) for the inverter side.

Later, these cost functions are used to compute the duty cycles which are calculated assuming that they are proportional to the inverse of the corresponding cost function value, where K_i is a constant to be determined:

$$\begin{aligned} d_{i0} &= K_i/g_{i0} \\ d_{i1} &= K_i/g_{i1} \\ d_{i2} &= K_i/g_{i2} \\ d_{i0} + d_{i1} + d_{i2} &= 1 \end{aligned} \tag{20}$$

With these duty cycles and cost function values, is defined a new cost function which is given by

$$g_{inv} = d_{i1}g_{i1} + d_{i2}g_{i2} \tag{21}$$

This is done at every sampling time for each of the six sectors. The pair of vectors that minimizes the cost function g_{inv} are selected as the optimal $\mathbf{v_i}^{opt}$ to be applied in the next period. The time that each vector is applied is given by:

$$\begin{aligned} t_{i0} &= d_{i0}T_s \\ t_{i1} &= d_{i1}T_s \\ t_{i2} &= d_{i2}T_s \end{aligned} \tag{22}$$

After obtaining the duty cycles and selecting the optimal vectors to be applied in both the rectifier and inverter, a switching pattern procedure, such as the one shown in Fig. 7, is adopted to apply the optimal vectors [15].

C. Relationship between the fictitious converter and the DMC

As it is necessary to apply the switching signals to the switches of the DMC, it is required to adapt the switching states of both input and output fictitious stages to the real one. This is given by the relationship between input and output stages and described as follows. As indicated in eq. (2), the relationship between the input voltage $\mathbf{v_i}$ and load voltage $\mathbf{v_o}$ depend on the state of the switching given by matrix $\mathbf{T}$. Based on the fictitious definition, the load voltage $\mathbf{v_o}$ is given as indicated in eq. (15). At the same time, the fictitious dc-link voltage v_{dc} is given by eq. (5). In summary,

$$\mathbf{v_o} = \begin{bmatrix} S_{i1} - S_{i4} \\ S_{i3} - S_{i6} \\ S_{i5} - S_{i2} \end{bmatrix} \begin{bmatrix} S_{r1} - S_{r4} & S_{r3} - S_{r6} & S_{r5} - S_{r2} \end{bmatrix} \mathbf{v_i} \tag{23}$$

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

$$\begin{bmatrix} S_{Aa} \\ S_{Ba} \\ S_{Ca} \\ S_{Ab} \\ S_{Bb} \\ S_{Cb} \\ S_{Ac} \\ S_{Bc} \\ S_{Cc} \end{bmatrix} = \begin{bmatrix} (S_{i1} - S_{i4})(S_{r1} - S_{r4}) \\ (S_{i1} - S_{i4})(S_{r3} - S_{r6}) \\ (S_{i1} - S_{i4})(S_{r5} - S_{r2}) \\ (S_{i3} - S_{i6})(S_{r1} - S_{r4}) \\ (S_{i3} - S_{i6})(S_{r3} - S_{r6}) \\ (S_{i3} - S_{i6})(S_{r5} - S_{r2}) \\ (S_{i5} - S_{i2})(S_{r1} - S_{r4}) \\ (S_{i5} - S_{i2})(S_{r3} - S_{r6}) \\ (S_{i5} - S_{i2})(S_{r5} - S_{r2}) \end{bmatrix} \tag{24}$$

IV. RESULTS

In order to validate the effectiveness of the proposed method, simulation results in Matlab-Simulink were carried out for both proposed techniques. The simulation parameters are shown in Table III and they consists in the available components in the laboratory. The input filter design is considered as a future work.

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 [μH]
T_s	Sampling time	50 [μs]
	Simulation step	1 [μs]

Fig. 8 and Fig. 9 show simulations results for the proposed indirect predictive controller when the minimization of the instantaneous input reactive power is considered. Before $t = 0.06$ [s] it is not included the active damping method in order to show that despite of the operation at fixed frequency, there exists a resonance of the input filter observing a source current i_{sA} in phase to its respective source voltage v_{sA} but with a THD of 18.55%. This is also reflected in the capacitor voltage v_A which presents also an oscillation due to the resonance of the filter Fig. 8(b). 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. After $t = 0.06$ [s], the active damping is implemented showing an improvement of both source current i_{sA} and capacitor voltage v_A, mitigating resonance effects. In this case the source current THD is improved to 5.30%. Fig. 9 shows the results for the load side where is observed that in both scenarios the currents $\mathbf{i_o}$ tracks very well its respective references $\mathbf{i_o}^*$ with a THD of 1.03% almost all the time. In this case the reference is established as I_o^*=12.5[A]@25[Hz]. In Fig. 9(b) is also observed the load voltage which is given as a function of the DMC switches and the input voltages $\mathbf{v_i}$.

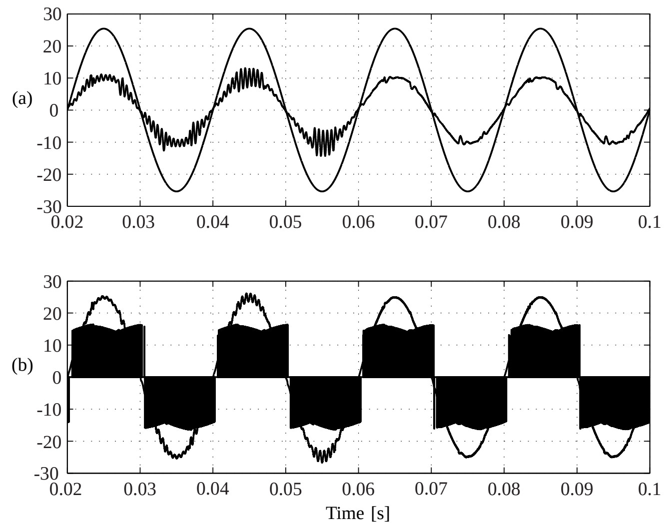

Fig. 8. Simulation results for Method I: minimization of instantaneous reactive power without (before $t = 0.06$ [s]) and with (after $t = 0.06$ [s]) active damping implementation: (a) source voltage v_{sA} [V/10] and source current i_{sA} [A]; (b) capacitor voltage v_A [V/10] and input current i_A [A].

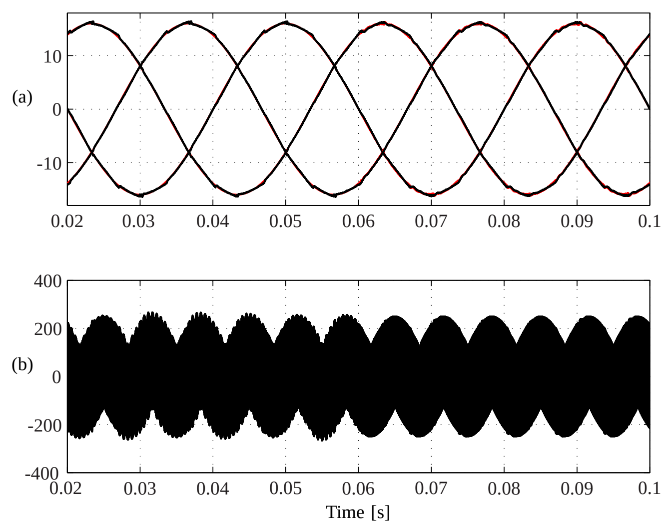

Fig. 9. Simulation results for Method I: minimization of instantaneous reactive power without (before $t = 0.06$ [s]) and with (after $t = 0.06$ [s]) active damping implementation:(a) load currents $\mathbf{i_o}$ [A] and its references $\mathbf{i_o}^*$ [A]; (b) load voltage v_a [V].

Fig. 10 and Fig. 11 show simulation results for the proposed indirect predictive controller when imposed source currents are considered in the input side. In this case, it is evident that this strategy presents a better performance than the previous cases with a source current i_{sA} in phase to its respective source voltage v_{sA} and a THD of 3.40% mitigating all the resonance of the input filter. On the load side, it is also observed a very good tracking of the load currents $\mathbf{i_o}$ to its respective references $\mathbf{i_o}^*$ with a THD of 0.89%.

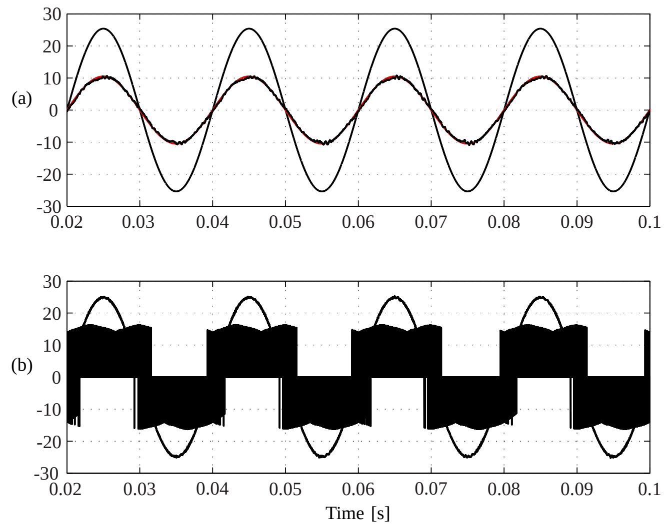

Fig. 10. Simulation results for Method II: imposed sinusoidal source currents: (a) source voltage v_{sA} [V/10] and source current i_{sA} [A]; (b) capacitor voltage v_A [V/10] and input current i_A [A].

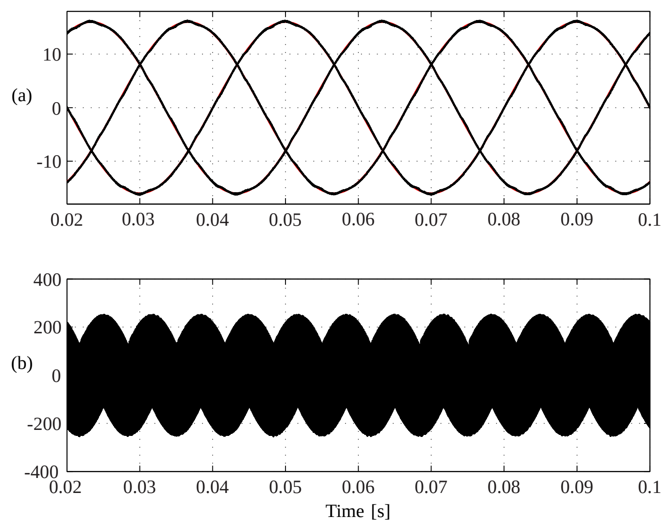

Fig. 11. Simulation results for Method II: imposed sinusoidal source currents: (a) load currents $\mathbf{i_o}$ [A] and its references $\mathbf{i_o}^*$ [A]; (b) load voltage v_a [V].

V. Conclusion

Two indirect predictive control strategies have been proposed for the direct matrix converter. The proposals use the idea of fictitious dc-link in order to separate the control of both input and output stages of the converter, being possible to reduce the complexity of the control, the operation at fixed switching frequency but also avoid the calculation of a weighting factors. The first method consists in a minimization of the instantaneous reactive input power which is enhanced with an active damping implementation to mitigate resonances of the input filter. The second method consists in to impose directly in the controller a sinusoidal waveform for the source current. Both methods mitigate the resonance of the filter but better performance is obtained with the second strategy. Experimental validation is considered as a future work.

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