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

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***Abstract*—In this paper an indirect model predictive current control strategy is proposed. The proposed method simplifies the computational cost while avoiding the use of weighting factors. Weighting factors are an issue for model predictive control in a direct matrix converter due to the large number of available switching states and necessity to control both input and output sides of the converter.**

***Keywords*—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	$[v_a\ v_b\ v_c]^T$
$\mathbf{i_o^*}$	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) features many advantages such as high power densities as well as harsh pressures and temperatures operating capability in comparison to the traditional back-to-back converter [1], [2]. The DMC provides bidirectional power flow and controllable input power factor as well as sinusoidal input and output currents ability.

Many modulation and control techniques have been successfully applied to the DMC, the most frequently used are Alesina -Venturini, Pulse Width Modulation (PWM), Space Vector Modulation (SVM) as well as Direct Torque Control (DTC) and Model Predictive Control (MPC) techniques [3]. The MPC technique has become a real alternative for the power converter modulation and control [4]. The mathematical model of the system is used in the MPC technique to predict the performance of the variables to be controlled in each valid switching state of the converter at every sampling time. In each sampling period, a given reference is compared with these predictions. Then, the switch state, which generates the minimal error between the reference and the prediction, will be the one chosen to be applied in the next sampling instant. Recently, the MPC applications are mainly focusing on multilevel converters [5], [6], shunt active power filters [7], PWM rectifiers [8], permanent magnet machines [9], as well as matrix converters [10]–[12] among others.

In [13], the STATCOM applications are using MPC in a DMC to compensate the lagging power factor loads. Another interesting MPC application is presented in [14], where the DMC MPC technique is fully implemented in a FPGA, reducing the complexity of hardware implementation as well as allowing fully paralleled control calculations.

However, there are still some issues which are regarded as an open topic for research even though the vast amount of progress of MPC for power converters. The input filter resonance due to the variable switching frequency is considered to be one of these issues. Since only one vector is chosen in one sampling period in the classical MPC, the variable switching frequency operation will cause high ripple on the controlled variables, especially when the resonance frequency of the input filter is close to the average switching frequency, which will affect the system performance as well as damage both the input and source currents waveforms.

In order to solve issues such as computational cost, weighting factor selections and the input filter resonance due to the operation at variable switching frequency, this paper proposes an indirect model predictive current control strategy.

The idea consists in emulating 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. The method is enhanced with an active damping implementation which consists of mimicking a damping resistor in parallel to the capacitor of the input filter.

II. MATHEMATICAL MODEL OF THE DMC

The DMC topology is presented in Fig. II. This ac to ac power converter includes nine bidirectional switches which connect the input side directly to the output load side without a dc-link storage device. An input filter is connected between the ac source and the bidirectional switches for two reasons:

- To prevent over-voltage hazard caused by the fast commutation of currents $\mathbf{i_i}$, which produces short-circuiting the impedance of the power supply.
- To eliminate the high-frequency harmonics inside the input $\mathbf{i_s}$.

Some rules have to be followed when operating the DMC converter: the load current cannot be interrupted abruptly due to the inductive nature of the load, and as the presence of capacitors in the input filter, the switches operation cannot short-circuit two input lines. These rules can be expressed by:

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

The input and output variables relations are defined by:

$$\mathbf{v_o} = \mathbf{T}\ \mathbf{v_i} \qquad (2)$$

$$\mathbf{i_i} = \mathbf{T}^T \mathbf{i_o} \qquad (3)$$

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

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

Equations (2) and (3) are the foundation of the whole modulation and control techniques, which can achieve the desired output voltages by choosing the appropriate combinations of switch states ON and OFF.

There are some techniques that use the concept of fictitious dc-link in order to simplify the modulation and control of the DMC. This idea was proposed by Rodriguez in the 80's to modulate the DMC in a simple way [1], [15]–[17]. The method consists in dividing the converter in a current source rectifier and a voltage source inverter linked by a fictitious dc-link such as represented in Fig. II.

The rectifier have six active current space vectors associated, which are represented in Fig. 3 (left), which are also featured 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 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.

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}

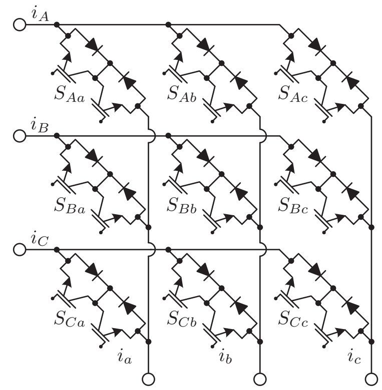

Fig. 1. Power circuit of the direct matrix converter.

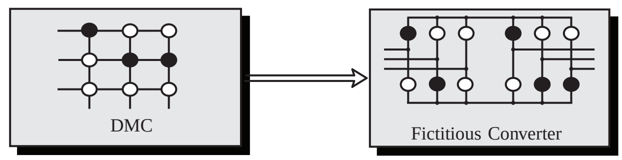

Fig. 2. Representation of the fictitious dc-link concept for the DMC.

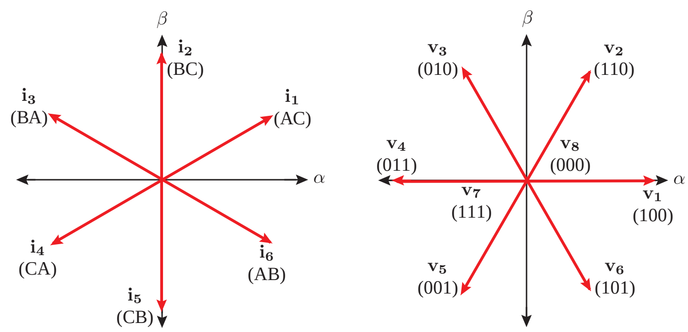

Fig. 3. Current and voltage space vectors of the fictitious converter. Left: current space vectors for the fictitious rectifier, right: voltage space vectors for the fictitious inverter.

TABLE 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 for the DMC with Active Damping Implementation

The main idea of the MPC for the DMC is represented in Fig. 4, where both input and output stages are controlled simultaneously using a predictive model of the instantaneous reactive input power and a predictive model of the load currents.

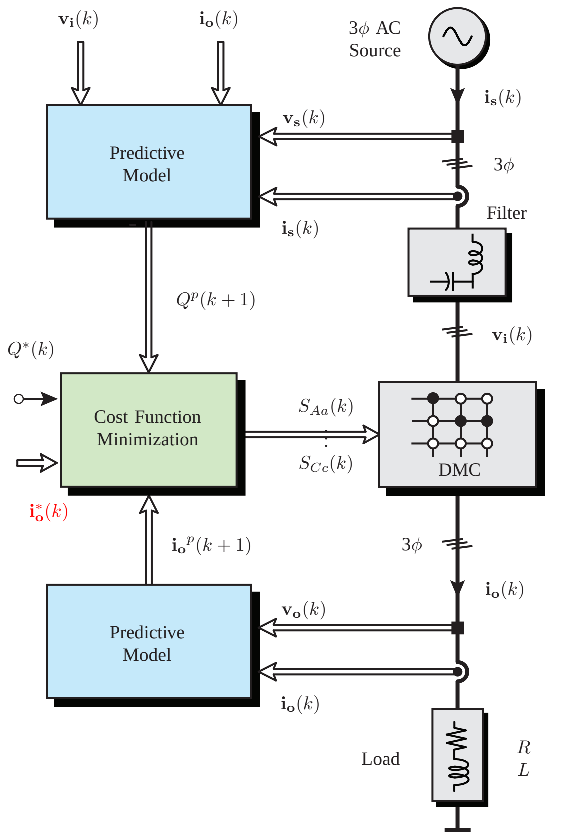

Fig. 4. Classic predictive current control strategy for the DMC.

These predictions are compared with their respective references in a single cost function g, which is normally expressed as:

$$g = \triangle i_o(k+1) + \lambda_q \triangle q_s(k+1) \tag{5}$$

where λ_q is the weighting factor for the minimization of the instantaneous reactive power, so it is necessary to determine the weighting factor in order to provide more priority to the instantaneous reactive input power or the load currents. The cost function is evaluated for each of the twenty-seven available switching states of the DMC, and the optimal switching state which will be applied to the converter in the next sampling instant, is selected by minimizing the cost function.

In this method two main issues are observed: first, the correct selection of a suitable weighting factor value is necessary in order to prioritise the control of the instantaneous reactive input power or the load currents and second, as the input stage and the output stage of the DMC are controlled simultaneously, and a large amount of twenty-seven available switching states is considered at every sampling time, thus a fast microcontroller is required for such high computational cost.

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 the weighting factors.

A. Control of the Rectifier

The control diagram of this stage is represented in Fig. 5. In the mathematical model of the rectifier stage, dc-link voltage v_{dc} is obtained as a function of the rectifier switches and the input phase voltage $\mathbf{v_i}$ as follows:

$$v_{dc} = \begin{bmatrix} S_{r1} - S_{r4} & S_{r3} - S_{r6} & S_{r5} - S_{r2} \end{bmatrix} \mathbf{v_i} \tag{6}$$

and the input currents $\mathbf{i_i}$ are defined as a function of the rectifier switches and the dc-link current i_{dc} as:

$$\mathbf{i_i} = \begin{bmatrix} S_{r1} - S_{r4} \\ S_{r3} - S_{r6} \\ S_{r5} - S_{r2} \end{bmatrix} i_{dc} \tag{7}$$

As shown in Fig. 3(left) and Table I, there are six active current space vectors which correspond to the valid switching states of the rectifier. The proposed scheme indicated in Fig. 5, is to control the input side of the DMC with all valid switching state and the mathematical relationship between input and output voltages and currents.

Similarly to the classical predictive strategy in the DMC, the rectifier includes an LC filter on the input side which is needed to prevent over-voltages and to provide filtering of the high-frequency components of the input currents produced by the commutations and the inductive nature of the load. The prediction model of the source current is as follows:

$$\frac{d\mathbf{i_s}}{dt} = \frac{1}{L_f}(\mathbf{v_s} - \mathbf{v_i}) - \frac{R_f}{L_f}\mathbf{i_s} \tag{8}$$

$$\frac{d\mathbf{v_i}}{dt} = \frac{1}{C_f}(\mathbf{i_s} - \mathbf{i_i}) \tag{9}$$

Since the predictive controller is formulated in discrete timing, a discrete time model is necessary for the load-converter system. By considering the guidelines presented in [18] 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:

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

B. Control of the Inverter

In the mathematical model of the inverter stage, dc-link current is obtained as a function of the inverter switches and the load current $\mathbf{i_o}$ as follows:

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

and the load voltage $\mathbf{v_o}$ are defined as a function of the inverter switches and the dc-link voltage v_{dc} as:

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

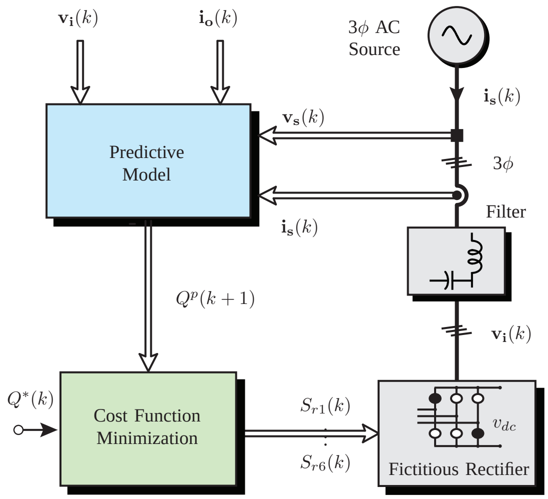

Fig. 5. Indirect predictive control strategy for the fictitious rectifier.

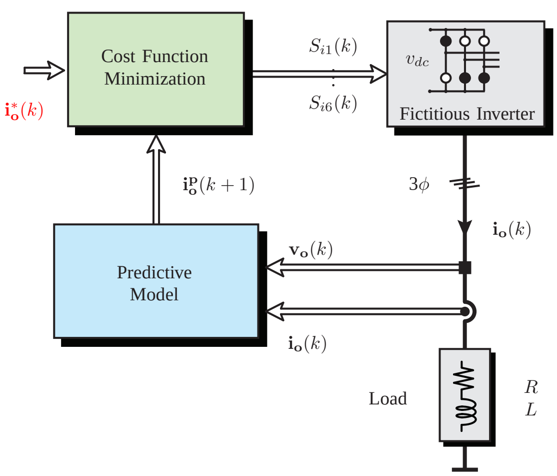

Fig. 6. Indirect predictive control strategy for the fictitious inverter.

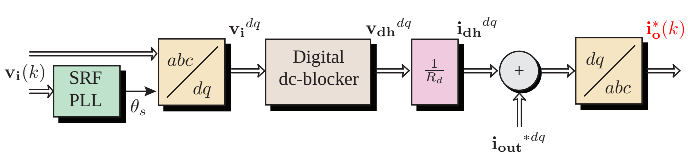

Fig. 7. Active damping implementation.

By assuming a passive RL load, the mathematical load model can be defined as:

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

Based on these definitions, the output current can be obtained using a forward Euler approximation in eq. (13), such 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:

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

The control diagram of this inverter 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 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 of the inverter, by modifying the load current reference as shown in Fig. 7 and indicated in [19], [20]. 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:

$$i_d = \frac{\mathbf{v_i}}{R_d} \tag{16}$$

The main advantages of this active damping implementation are as follows:

- Easy to implement.
- Do not affect the efficiency of the converter.
- Do not involve additional measurements or any modification to the predictive algorithm.

C. Relationship between the fictitious converter and the DMC

As in a real scenario, the switching signals are applied to the switches of DMC, making it necessary to adapt the switching states of both input and output fictitious stages to the real signals. As shown in eq. (2) and eq. (3), the relations between the input and output variables of the DMC are defined with the instantaneous transfer matrix $\mathbf{T}$. Based on the fictitious definition, *dc*-link voltage v_{dc} is obtained from the input phase voltages $\mathbf{v_i}$ in eq. (6), and the load voltage $\mathbf{v_o}$ is obtained from *dc*-link voltage v_{dc} in eq. (12). 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 in both steady and transient conditions. The simulation parameters are shown in Table III. Fig. 8 and Fig. 9 show simulations results for the proposed indirect predictive controller. Before $t = 0.06$[s], the control strategy is evaluated without the active damping implementation.

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	30 [μs]
	Simulation step	1 [μs]

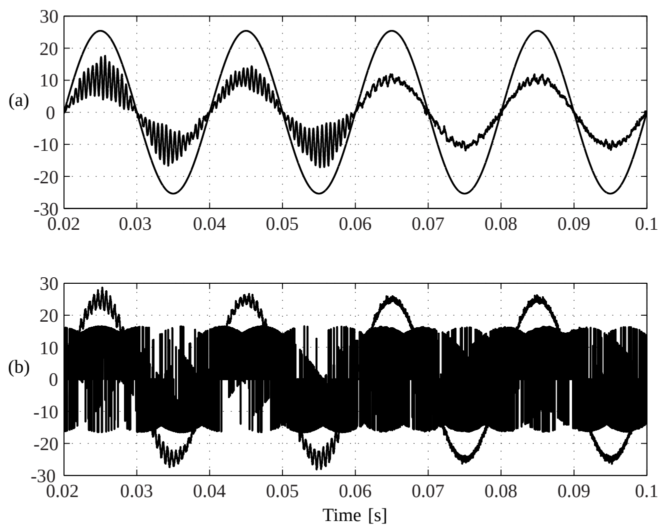

Fig. 8. Simulation results of the proposed method. Before $t = 0.06$ [s] without active damping, after $t = 0.06$ [s] with active damping implementation: (a) source voltage v_{sA} [V/10] and source current i_{sA} [A]; (b) capacitor voltage v_A [V/10] and input current i_A [A].

After $t = 0.06$[s], the control strategy is evaluated with the implementation of the active damping technique. In Fig. 8(a) one can observe 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 61.10%. After the implementation of the active damping method, the source current is improved obtaining almost a sinusoidal waveform with a THD of 8.03%. 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 that the commutated input current i_A, which is given as function of the DMC switches and the load currents $\mathbf{i_o}$. A highly satisfactory tracking of the load currents $\mathbf{i_o}$ to its respective references $\mathbf{i_o^*}$ is noted in Fig. 9(a) with a sinusoidal waveform and a THD of 0.86% and 1.26% 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 $\mathbf{v_i}$.

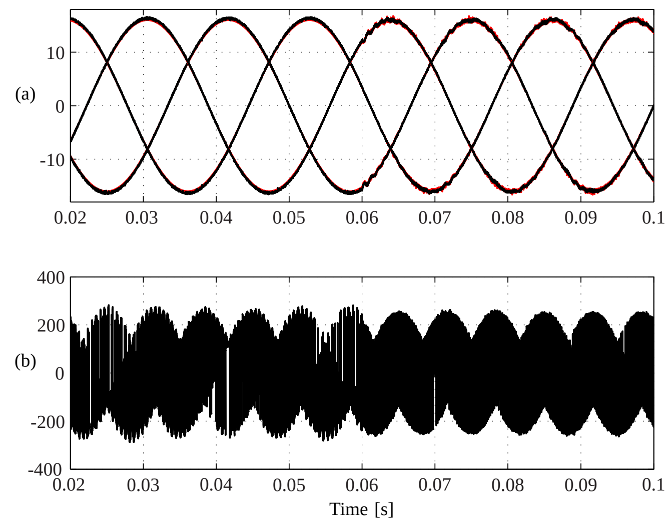

Fig. 9. Simulation results of the proposed method. Before $t = 0.06$ [s] without active damping, after $t = 0.06$ [s] with active damping implementation: (a) load currents $\mathbf{i_o}$ [A] and its references $\mathbf{i_o}^*$ [A]; (b) load voltage v_a [V].

V. CONCLUSION

This paper has presented an indirect model predictive current control strategy with minimization of the instantaneous reactive input power for a direct matrix converter wich has been enhanced with an active damping implementation. The method uses 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 is possible to mitigate the resonances of the input filter in both input currents and input voltages, improving the performance of the full system. By considering the proposed strategy, a new alternative has emerged for the control of both the input and load currents in a direct matrix converter.

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