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Indirect Model Predictive Current Control Techniques for a Direct Matrix Converter

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

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

***Abstract*—The direct matrix converter has twenty-seven available switching states which 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 of the converter. 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. Both methods are 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 proposed techniques demonstrating that they are an alternative to classical predictive control strategies for the direct matrix converter.**

***Index Terms*—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	
$\mathbf{i}$	Load current	$[i_a\ i_b\ i_c]^T$
$\mathbf{v}$	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 to traditional back-back converter, the direct matrix converter (DMC) provides a compact, high power density and reliable ac/ac solution [1]. Due to the stated benefits, the DMC has been employed in various aerospace and military applications [1]. Some of the renowned modulation and control techniques, that have been applied to the DMC, are Venturini Modulation, Pulse Width Modulation (PWM), Space Vector Modulation (SVM), Direct Torque Control (DTC) and Model Predictive Control (MPC) [2]. MPC has emerged as a real alternative for the control of power converters [3]. MPC utilizes mathematical model of the system to predict the optimal switching state to be applied in the next sampling period. The optimal switching state is the one which minimizes cost function in order to achieve certain control objectives by calculating the cost function against all of the valid switching states of the converter. This implies that a converter with higher number of switching states, such as in DMC with a total of 27 switching states, will possibly require exceptional computational power. In this paper an indirect model predictive current control strategy is proposed which avoids the weighting factors by defining separate cost functions for each of the control objectives. The idea is to consider DMC as a two stage converter linked by a fictitious dc-link allowing a parallel and independent control of input and output stages, therefore avoiding the use of weighting factors. Two methods are proposed in this paper. Both methods have a load current control but the first method considers the minimization of the instantaneous reactive input power and the second, imposes a sinusoidal source current on the input side.

II. MATHEMATICAL MODEL OF THE DMC

The DMC, shown in FIg. 1, is a direct ac/ac converter composed of bidirectional switches. Between the ac source and bidirectional switches, an input filter is connected for two purposes: to prevent over-voltage due to fast commutation of currents $\mathbf{i_i}$, which produces short-circuiting the power supply and to eliminate high-frequency harmonics in the input currents $\mathbf{i_s}$. Due to the voltage source at the input and the current source at the output, constraints of the converter ca 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 [4], [5].

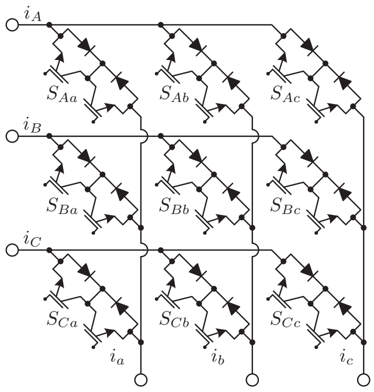

Fig. 1. Power circuit of the direct matrix converter.

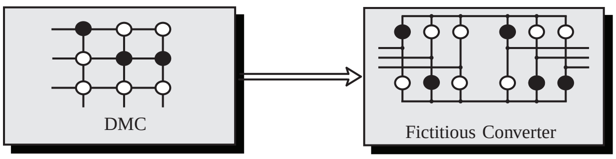

Fig. 2. Representation of the fictitious dc-link concept for the DMC.

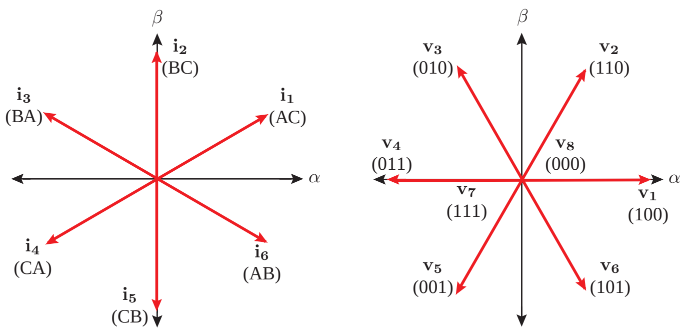

Fig. 3. Current and voltage space vectors of the fictitious converter. Left: current space vectors for the fictitious rectifier, right: voltage space vectors for the fictitious inverter.

The method consist 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. 2. The rectifier have associated six active current space vectors which are represented in Fig. 3 (left). The inverter has associated eight voltage space vectors which are represented in Fig. 3 (right). 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.

III. Proposed Indirect Model Predictive Control Method for the DMC

The control diagram of the proposed technique are represented in Fig. 4 and Fig. 5, respectively. The mathematical model of the rectifier stage has the input phase voltages $\mathbf{v_i}$ and fictitious dc-link current i_{dc} as inputs and the fictitious dc-link voltage v_{dc} and input currents $\mathbf{i_i}$ as outputs. This is shown in equations (5) and (6), respectively:

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

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

As indicated in Fig. 3 (left), 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 controlling the input side of the converter by considering these available switching states and considering the mathematical relationship between input and output voltages and currents.

Similar to the classical predictive strategy in the DMC, for the control of the input side it is necessary to have the prediction model of the source current given by:

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

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

Since the predictive controller is formulated in discrete time, it is necessary to derive a discrete time model for the load-converter system. From [6], the cost function for the input reactive power minimization method i.e. g_r is defined as;

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

For the imposed sinusoidal source current method, the cost function g_r is defined as:

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

In the first method, the reference of the instantaneous reactive power minimization is defined as $Q^*(k)=0$ and for the second method i.e. imposing the sinusoidal source current, it is recommend to review [7] in order to define the source current references $\mathbf{i}^*_{\mathbf{s}}(k)$.

The control diagram of the inverter stage is represented in Fig. 5. For the mathematical model of the inverter it is considered the output currents $\mathbf{i}$ and fictitious dc-link voltage v_{dc} as inputs, and the fictitious dc-link current i_{dc} and the output voltage $\mathbf{v}$ as outputs. This can be seen in equations (11) and (12), respectively:

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

$$\mathbf{v} = \begin{bmatrix} S_{i1}-S_{i4} \\ S_{i3}-S_{i6} \\ S_{i5}-S_{i2} \end{bmatrix} v_{dc} \qquad (12)$$

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

$$\mathbf{v} = L\frac{d\mathbf{i}}{dt} + R\mathbf{i} \qquad (13)$$

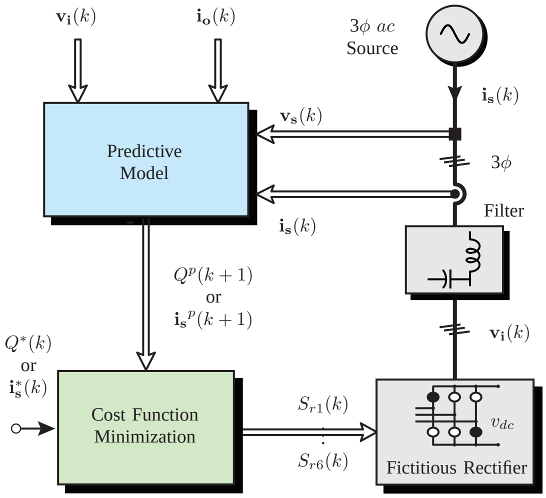

Fig. 4. Indirect predictive control strategy for the fictitious rectifier.

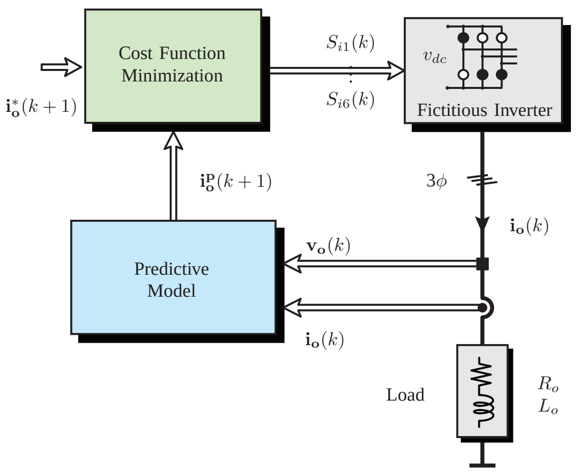

Fig. 5. Indirect predictive control strategy for the fictitious inverter.

With these definitions, it is possible to define the prediction model of the output side using a forward Euler approximation in eq. (13), such as:

$$\mathbf{i}(k+1) = c_1\mathbf{v}(k) + c_2\mathbf{i}(k) \quad (14)$$

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:

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

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 $\mathbf{v}$ depend 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,

$$\mathbf{v} = \begin{bmatrix} S_{i1} - S_{i4} \\ S_{i3} - S_{i6} \\ S_{i5} - S_{i2} \end{bmatrix} \begin{bmatrix} S_{r1} - S_{r4} & S_{r3} - S_{r6} & S_{r5} - S_{r2} \end{bmatrix} \mathbf{v_i} \quad (16)$$

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

$$\begin{bmatrix} S_{Aa} \\ S_{Ba} \\ S_{Ca} \\ S_{Ab} \\ S_{Bb} \\ S_{Cb} \\ S_{Ac} \\ S_{Bc} \\ S_{Cc} \end{bmatrix} = \begin{bmatrix} (S_{i1} - S_{i4})(S_{r1} - S_{r4}) \\ (S_{i1} - S_{i4})(S_{r3} - S_{r6}) \\ (S_{i1} - S_{i4})(S_{r5} - S_{r2}) \\ (S_{i3} - S_{i6})(S_{r1} - S_{r4}) \\ (S_{i3} - S_{i6})(S_{r3} - S_{r6}) \\ (S_{i3} - S_{i6})(S_{r5} - S_{r2}) \\ (S_{i5} - S_{i2})(S_{r1} - S_{r4}) \\ (S_{i5} - S_{i2})(S_{r3} - S_{r6}) \\ (S_{i5} - S_{i2})(S_{r5} - S_{r2}) \end{bmatrix} \quad (17)$$

IV. Results

To validate the effectiveness of the proposed method, simulation results in Matlab-Simulink were carried out. The simulation parameters are C_f=21 [μF], L_f=400 [μH], R_f=0.5 [Ω], R=10 [Ω], L=10 [mH], T_s=10 [μs] and a simulation step of 1 [μs]. A step change in the load current is applied to the converter in order to evaluate the performance of the proposed strategy in terms of dynamic response. This analysis is done as depicted from Fig. 6 to Fig. 9. In Fig. 6 are shown the input variables where is observed a resonance of the input filter due to the current step variation, Fig. 6(a). This effect is not evidenced when an imposed waveform is established in the controller (Method II) such as shown in Fig. 8(a). In both cases and despite of the resonance for the first case (Method I), it is also evident the good performance of the input filter which mitigates almost all the high harmonic frequencies observed in Fig. 6(b) and Fig. 8(b) which are produced by the commutation of the switches. In Fig. 7(a) and Fig. 9(a) is observed a good dynamic response of the load current $\mathbf{i_o}$ to its respective reference $\mathbf{i_o^*}$ with a very fast dynamic response and a very good tracking of the load current. The step change is from I_o^*=10[A]@150Hz to I_o^*=12.5[A]@50Hz.

V. Conclusion

In this paper, indirect model predictive current control strategies for a direct matrix converter has been presented.

Both methods use the idea of fictitious dc-link to separate the control of both input and output stages of the converter, reducing the control complexity and excessive computations required in determining the correct weighting factors for input and output currents. The method with an imposed sinusoidal source current at the input side not only eliminates the effect of input filter resonances but also presents better dynamic results in transient state.

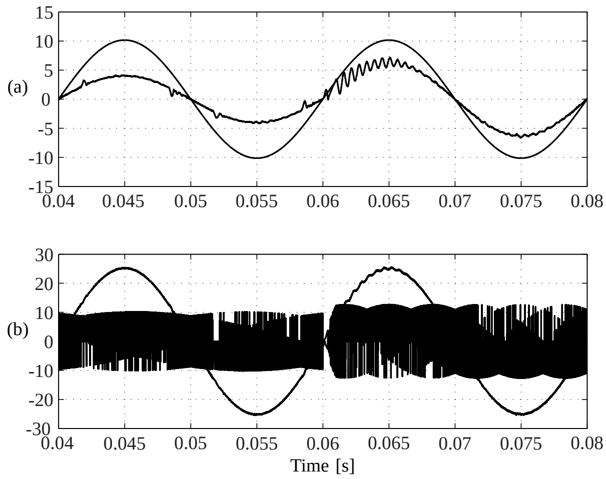

Fig. 6. Simulation results of the proposed method in transient state (Method I): (a) source voltage v_{sA} [V/25] and source current i_{sA} [A]; (b) capacitor voltage v_A [V/10] and input current i_A [A].

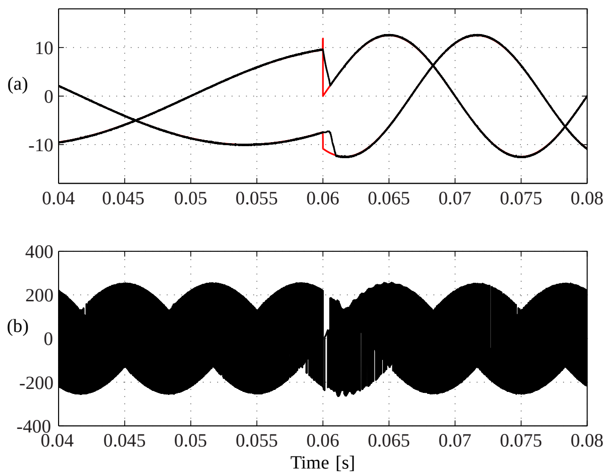

Fig. 7. Simulation results of the proposed method in transient state (Method I): a) load currents $\mathbf{i_o}$ [A]; b) load voltage v_a [V].

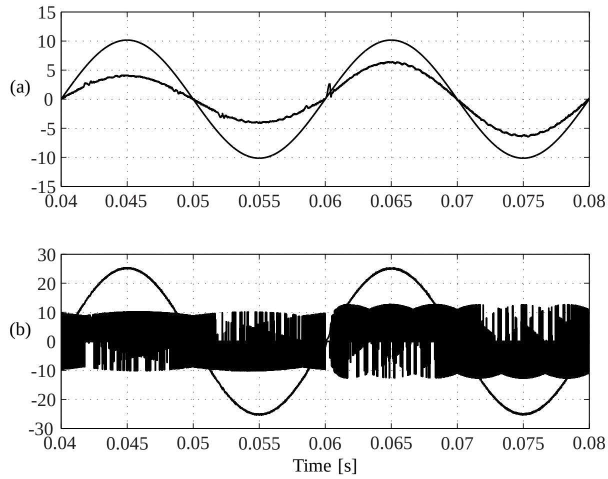

Fig. 8. Simulation results of the proposed method in transient state (Method II): (a) source voltage v_{sA} [V/25] and source current i_{sA} [A]; (b) capacitor voltage v_A [V/10] and input current i_A [A].

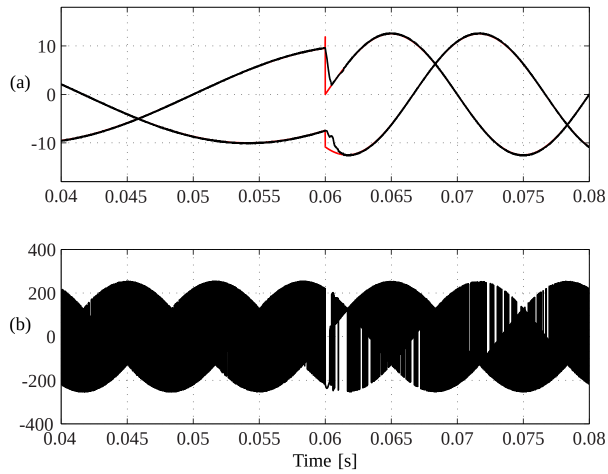

Fig. 9. Simulation results of the proposed method in transient state (Method II): a) load currents $\mathbf{i_o}$ [A]; b) load voltage v_a [V].

By considering the proposed strategy, it is possible to tune the weighting factors in a multiple objective cost function without requiring excessive computational power.

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