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Modulated Model Predictive Current Control of an Indirect Matrix Converter with Active Damping

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***Abstract*—A modulated model predictive control (M²PC) scheme for an indirect matrix converter is proposed in this paper, including an active damping method to mitigate the input filter resonance. The control strategy allows the instantaneous power control and the output current control at the same time, operating at a fixed frequency. An optimal switching pattern is used to emulate the desired waveform quality features of space vector modulation and achieve zero-current switching operations. The active damping technique emulates a virtual resistor which damps the filter resonance. Simulation results present a good tracking to the output-current references, unity input displacement power factor, the low input-current distortions and a reduced common-mode voltage (CMV).**

Keywords—Matrix converter, modulated model predictive control, unity input displacement power factor, active damping

I. Introduction

Matrix converter (MC) is a simple and compact power circuit that directly connects the ac-source with any arbitrary ac-load without the need for large storage elements, making this topology suitable for many applications where weight and size are important issues [1]–[4]. MC can be classified into direct matrix converter (DMC) and indirect matrix converter (IMC). Although DMC and IMC have different topologies and commutation, they actually have the same input-output transfer function [1], [2]. Their topologies, control strategies, applications and trends have been frequently investigated during the past years worldwide [5]–[8]. The major drawback of MC is the increased control complexity due to the lack of storage stage elements and the large number of switching states [9], many control strategies and modulations have been studied for MC, such as the venturini method, scalar method, carrier based PWM, space vector modulation (SVM), direct torque control, direct power control and so on. The SVM method utilizes the instantaneous space vectors to represent the input and output voltages and currents, the input-current vector and the output-voltage vector are determined by switching configurations of MC, and the magnitudes of these vectors are decided by the instantaneous values of the input voltages and the output currents. SVM is inherently capable of realizing complete control of both the output-voltage vector and the instantaneous input-current displacement angle [4].

However with the rapid development of high-performance digital processors and power devices, SVM is now being challenged by model predictive control strategy (MPC) which provides many advantages such as the capability of including non-linearities and various constraints of the MC system, the capability of easier implementation, the capability of easier modification depend on specific applications and so on [10]–[13]. MPC is an optimization algorithm where a model of the MC system is considered in order to predict its future behavior over a horizon in time, and a sequence of future actions is then obtained by minimizing a cost function representing the desired behavior of the MC system. However due to the lack of modulation, one of the main drawbacks of MPC is that the control algorithm only selects and applies one switching state for the whole sampling instant which generates noise as well as large current and voltage ripples, the variable switching frequency leads to a spread spectrum, decreasing the performance of the system in terms of power quality [14]–[18].

To solve these problems, the modulated model predictive control (M²PC) algorithm has been introduced and applied to several power converters structures [19]–[21]. The M²PC combines the positive features of both SVM and MPC to obtain a model predictive control based algorithm with an intrinsic modulation scheme. In M²PC, the IMC system is divided into the rectifier stage and the inverter stage which are considered separately, the switching frequency of M²PC is constant by selecting two active vectors for the rectifier stage and three active vectors (zero vector included) for the inverter stage within a fixed switching instant.

On the other hand, compared with SVM the model predictive control strategy is more likely to excite the input filter resonance due to potential harmonics in the ac-source and the converter itself, leading to poorer source current waveforms [22]–[24]. Both passive and active damping control methods are suitable solutions, while the latter has a better performance with higher efficiency and easier implementation [25]. The basic idea of active damping strategy can be obtained from [26], [27], the method emulates a virtual damping resistor placed in parallel with the capacitor to make the harmonic currents caused by the resonance flow through the virtual damping resistor.

The main contribution of this paper is the improvement of the source current, a good tracking to the output-current references, the minimization of instantaneous reactive power and a reduction of CMV in the IMC system. The improvement of the source current is achieved by the implementation of active damping, a fixed switching frequency, a good tracking to the output-current references is guaranteed in the cost

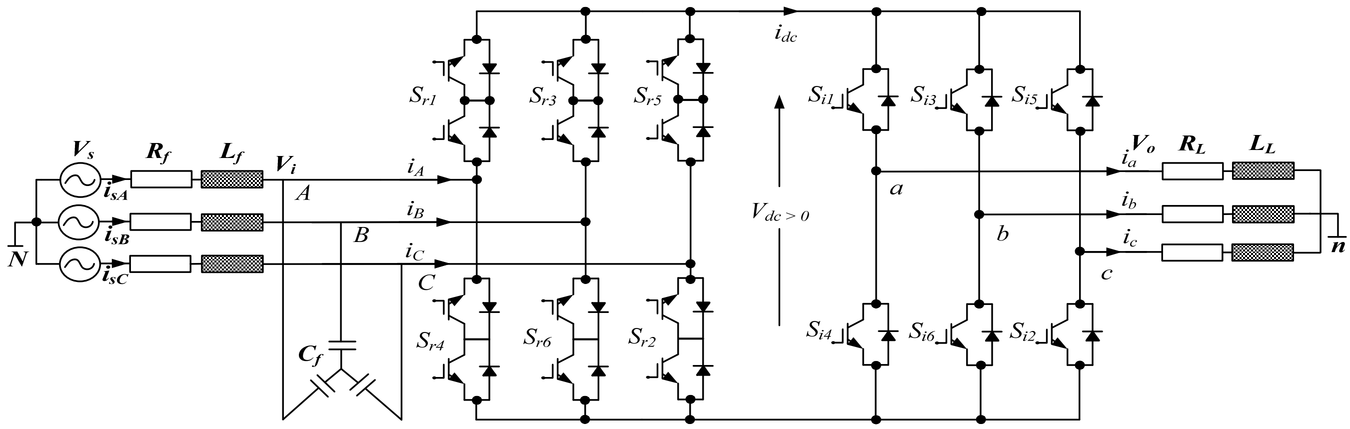

Fig.1 Power circuit of the indirect converter

function of the inverter stage, the minimization of instantaneous reactive power is realized in the cost function of the rectifier stage, the optimal switching pattern contributes to the zero-current switching operations for the rectifier stage, simplifying the commutation strategy of the IMC. Simulation results for a three-phase IMC system are presented to validate the proposed approach.

II. INDIRECT MATRIX CONVERTER MODEL

The topology of the IMC is presented in Fig.1. The converter consists of the rectifier stage and the inverter stage, this configuration takes advantage of a safe operation of the converter and a reduction of the switching losses when using the zero dc-link current switching scheme.

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 V_i as follows:

$$V_{dc} = [S_{r1} - S_{r4} \;\; S_{r3} - S_{r6} \;\; S_{r5} - S_{r2}]V_i \tag{1}$$

Where S_{ri} ($i \in \{1,2,3,4,5,6\}$) represents the switching function of the six switches in the rectifier stage, whose value is 1 for closed state and 0 for open state. Respectively, the input currents i_i are defined as a function of the rectifier switches and the dc-link current i_{dc} as:

$$i_i = \begin{bmatrix} S_{r1} - S_{r4} \\ S_{r3} - S_{r6} \\ S_{r5} - S_{r2} \end{bmatrix} i_{dc} \tag{2}$$

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

$$i_{dc} = [S_{r1} - S_{r4} \;\; S_{r3} - S_{r6} \;\; S_{r5} - S_{r2}]i_o \tag{3}$$

Besides, the load voltage V_o is defined as a function of the inverter switches and the dc-link voltage V_{dc} as

$$V_o = \begin{bmatrix} S_{i1} - S_{i4} \\ S_{i3} - S_{i6} \\ S_{i5} - S_{i2} \end{bmatrix} V_{dc} \tag{4}$$

For the safety operation of IMC, the following three conditions are mandatory to be met [22], [23]:

- Any two input phases cannot be short-circuited.
- Any one output phase cannot be open-circuited.
- The dc-link voltage must be positive.

According to these constraints, at every sampling time, only three of the nine valid switching states are considered. Besides, an input filter is needed for the prevention of over-voltages and harmonics distortions. The filter consists of a second-order low-pass system as follows:

$$\frac{di_s}{dt} = \frac{1}{L_f}(V_s - V_i) - \frac{R_f}{L_f} i_s \tag{5}$$

$$\frac{dV_i}{dt} = \frac{1}{C_f}(i_s - i_i) \tag{6}$$

Respectively, the load mathematical model is given as:

$$V_o = L_L \frac{di_o}{dt} + R_L i_o \tag{7}$$

III. MODULATED MODEL PREDICTIVE CURRENT CONTROL OF AN INDIRECT MATRIX CONVERTER

To overcome the drawbacks of the traditional MPC like the lack of modulation and the variable switching frequency [28], The M^{2}PC strategy is proposed for the IMC system shown in Fig 2. Initially, the M^{2}PC strategy evaluates the rectifier stage and the inverter stage separately, the reactive power prediction and the output current prediction generate $q_s(k+1)$ and $i_o(k+1)$ which are the predicted reactive power and output current at the $(k+1)^{th}$ sampling instant. Then with the reference of reactive power q_s^* and output current i_o^*, the input and output cost function pursue the selection of the switching states of the rectifier and inverter stage which lead to the respective reference at the end of the sampling period. Finally, a switching sequence is arranged in a symmetrical manner similar to that used in the SVM scheme. Unlike traditional MPC where one voltage vector is applied for the entire sampling period, M^2PC selects two best active vectors for the rectifier stage and three best active vectors (zero vector included) for the inverter stage. The M^2PC strategy is presented in details in the following sections:

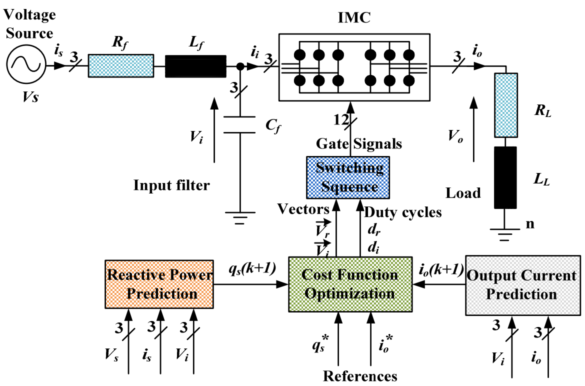

Fig. 2 Block Diagram of M^2PC for the IMC system

A. Models in Discrete Time

Since the model predictive controller is formulated in discrete time, it is necessary to derive a discrete time model for the rectifier stage. By using the general forward-difference euler formula, the rectifier stage can be represented by a state-space model with the state variables i_s and V_i obtained from eq. (8)-(12):

$$\begin{bmatrix} i_s(k+1) \\ V_i(k+1) \end{bmatrix} = \Phi_i \begin{bmatrix} i_s(k) \\ V_i(k) \end{bmatrix} + \Gamma_i \begin{bmatrix} V_s(k) \\ i_i(k) \end{bmatrix} \tag{8}$$

$$\text{Where, } \Phi_i = e^{A_i T_s},\ \Gamma_i = A_i^{-1}(\Phi_i - I)B_i \tag{9}$$

$$A_i = \begin{bmatrix} -R_f/L_f & -1/L_f \\ 1/C_f & 0 \end{bmatrix},\ B_i = \begin{bmatrix} 1/L_f & 0 \\ 0 & -1/C_f \end{bmatrix} \tag{10}$$

R_f, L_f and C_f are the parameters of the input filter and T_s is the sampling time. Similarly, the discrete state-space equation for the output stage, having the output current i_o as the single state variable, is described as follows :

$$i_o(k+1) = \Phi_o i_o(k) + \Gamma_o V_o(k) \tag{11}$$

$$\Phi_o = e^{-\frac{R_L}{L_L}T_s},\ \Gamma_o = -\frac{1}{R_L}(\Phi_o - 1) \tag{12}$$

where L_L and R_L represents the load inductance and resistance, respectively. Equations (8) and (11) are used to predict the values of the state variables at the $(k+1)^{th}$ sampling instant and are calculated for every possible switching states of the rectifier stage and the inverter stage.

B. Cost Function Minimization

For the rectifier stage, the M^2PC algorithm considers two active vectors and evaluates two cost functions respectively with all the valid switching states giving a positive dc-link voltage for the IMC. For example, g_{r1} is defined as the cost function of vector V_{r1} for the first prediction and g_{r2} is defined as the cost function of the next adjacent vector V_{r2} for the second prediction, with the evaluation of each cost function, the duty cycles d_{r1}, d_{r2} associated to vectors V_{r1}, V_{r2} can be calculated as follows:

$$\begin{aligned} d_{r1} &= g_{r2}/(g_{r1}+g_{r2}) \\ d_{r2} &= g_{r1}/(g_{r1}+g_{r2}) \\ d_{r1} &+ d_{r2} = 1 \end{aligned} \tag{13}$$

Where the cost function g_r denotes the error between the reference and the predicted value of the instantaneous reactive power in the $(k+1)^{th}$ sampling time. The reference is set to zero ($q_s^* = 0$) to realize the instantaneous reactive power minimization on the input side

$$g_r = (q_s^* - (v_{s\alpha}(k+1)i_{s\beta}(k+1) - v_{s\beta}(k+1)i_{s\alpha}(k+1)))^2 \tag{14}$$

With these duty cycles, it is possible to evaluate the total cost function g_r at every sampling instant:

$$g_r = d_{r1}g_{r1} + d_{r2}g_{r2} \tag{15}$$

For the inverter stage, the implementation is similar as that for the rectifier stage, while a zero vector V_{i0} must be considered in addition to two adjacent vectors V_{i1}, V_{i2} . For example, g_{i1} is defined as the cost function of vector V_{i1} and g_{i2} is defined as the cost function of the next adjacent vector V_{i2} ,with the evaluation of each cost function, the duty cycles d_{i0} , d_{i1} , d_{i2} associated to vectors V_{i0} , V_{i1} , V_{i2} can be calculated by:

$$\begin{aligned} d_{i0} &= g_{i1}g_{i2}/(g_{i0}g_{i1}+g_{i0}g_{i2}+g_{i1}g_{i2}) \\ d_{i1} &= g_{i0}g_{i2}/(g_{i0}g_{i1}+g_{i0}g_{i2}+g_{i1}g_{i2}) \\ d_{i2} &= g_{i0}g_{i1}/(g_{i0}g_{i1}+g_{i0}g_{i2}+g_{i1}g_{i2}) \\ d_{i0} &+ d_{i1} + d_{i2} = 1 \end{aligned} \tag{16}$$

Where the cost function g_i represents the error between the predicted values and the reference values of the output currents.

$$g_i = (i_o^* - i_o(k+1))^2 \tag{17}$$

With these duty cycles, it is possible to evaluate the total cost function g_i at every sampling period:

$$g_i = d_{i0} g_{i0} + d_{i1} g_{i1} + d_{i2} g_{i2} \tag{18}$$

C. Optimal Switching Pattern

An optimal switching pattern is selected to obtain the expected unity input displacement power factor and output currents because of the absence of dc-link energy storage elements [28]. The optimal switching pattern proposed in this paper is shown in Fig. 3.

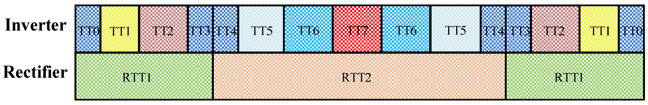

Fig. 3 Optimal switching pattern

In this optimal pattern, the switching sequences of the IMC are closely coupled. The resulting duty cycles $TT0 \sim TT7$ associated with the states of the inverter stage are calculated by:

$$\begin{cases} TT0 = TT3 = TT4 = \dfrac{1}{8} d_{i0} \\ TT1 = \dfrac{1}{2} d_{i1} d_{r1} \\ TT2 = \dfrac{1}{2} d_{i2} d_{r1} \\ TT5 = \dfrac{1}{2} d_{i2} d_{r2} \\ TT6 = \dfrac{1}{2} d_{i1} d_{r2} \\ TT7 = \dfrac{1}{4} d_{i0} \end{cases} \tag{19}$$

Besides, the duty cycles $RTT1 \sim RTT2$ associated with the commutation of the rectifier stage is equal to

$$\begin{cases} RTT1 = TT0 + TT1 + TT2 + TT3 \\ RTT2 = 2(TT5 + TT6 + TT7) \end{cases} \tag{20}$$

It is clear from (19) and (20) the state commutation of the rectifier stage always happens when the dc-link current i_{dc} is zero, since the zero voltage stage is applied to the inverter stage at that moment. This means that the zero-current switching operations are guaranteed for the rectifier stage, simplifying the commutation strategy of the IMC.

IV. Active Damping Strategy

In order to mitigate the potential resonance of the input filter excited by potential harmonics in the ac-source and the IMC itself, an active damping strategy is added to the M^2PC IMC system, the proposed active damping technique is indicated in Fig. 4.

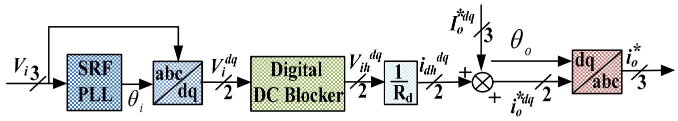

Fig. 4 Active damping implementation

The method considers a virtual harmonic resistive damper R_d placed in parallel with the input filter capacitor , immune to system parameter variations, to suppress the system harmonics without affecting the fundamental component [26], [27]. The input voltage V_i is considered in *dq* axes, deleting the fundamental element and considering only the harmonic components by passing through a digital *dc*-blocker filter, the transformation of *abc* to *dq* axes is realized by a synchronous-reference-frame phase-locked loop, then the damping harmonic currents are calculated by:

$$\begin{bmatrix} i_{dh}^d \\ i_{dh}^q \end{bmatrix} = \frac{1}{R_d} \begin{bmatrix} V_{ih}^d \\ V_{ih}^q \end{bmatrix} \tag{21}$$

Where $V_{ih}^{dq} = \left[V_{ih}^d \; V_{ih}^q \right]^T$ represents all harmonic components in V_i, then the new output-current reference is expressed by:

$$\begin{bmatrix} i_o^{*d} \\ i_o^{*q} \end{bmatrix} = \begin{bmatrix} I_o^{*d} \\ I_o^{*q} \end{bmatrix} + \begin{bmatrix} i_{dh}^d \\ i_{dh}^q \end{bmatrix} \tag{22}$$

Where $i_o^{*dq} = \left[i_o^{*d} \; i_o^{*q} \right]^T$, and $I_o^{*dq} = \left[I_o^{*d} \; I_o^{*q} \right]^T = \left[I_o^* \; 0 \right]^T$ is the reference of output current in *dq* axes.

V. Simulation Results

In order to validate the performance of the proposed method, simulation results in Matlab-Simulink have been carried out and the parameters of the simulation model are shown in Table I.

TABLE I. SIMULATION PARAMETERS

V_s	Ac-voltage amplitude	311[V]
L_f	Input filter inductor	400[μH]
R_f	Input filter resistor	0.5[Ω]
C_f	Input filter capacitor	21[μF]
L_L	Load inductor	10[mH]
R_L	Load resistor	10[Ω]
T_s	Sampling time	20[μs]
f_s	Switching frequency	50[kHz]
	Simulation step	1[μs]

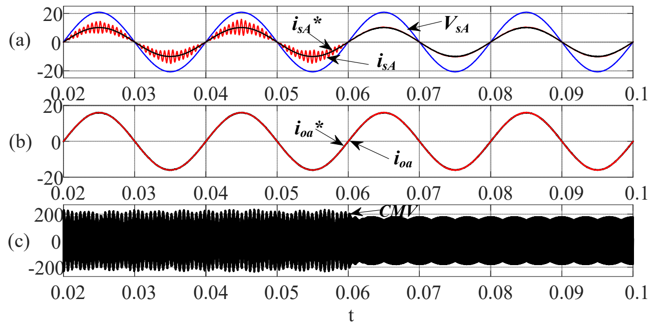

Fig. 5. Simulation results of M²PC strategy for the IMC, where output-current reference amplitude is set to 16[A] and output-current frequency is set to 50[Hz]: before t = 0.06[s] without active damping, after t = 0.06[s] with active damping: (a) source voltage V_{sA} / 15 [V], source-current reference i_{sA}^* [A] and source current i_{sA} [A]; (b) output-current reference i_{oa}^* [A] and output current i_{oa} [A]; (c) common-mode voltage CMV [V].

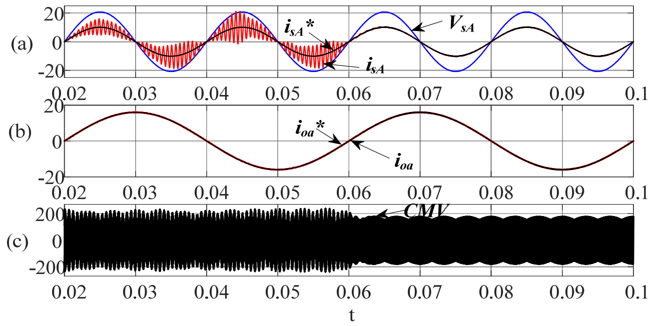

Fig. 6. Simulation results of M²PC strategy for the IMC, where output-current reference amplitude is set to 16[A] and output-current frequency is set to 25[Hz]: before t = 0.06[s] without active damping, after t = 0.06[s] with active damping: (a) source voltage V_{sA} / 15 [V], source-current reference i_{sA}^* [A] and source current i_{sA} [A]; (b) output-current reference i_{oa}^* [A] and output current i_{oa} [A]; (c) common-mode voltage CMV [V].

Fig. 5(a) shows the measured source voltage, the source-current reference and the measured source current of phase a, Fig. 5(b) demonstrates the reference and the measured output current of phase a, and the common-mode voltage is shown in Fig. 5(c). From Fig. 5(a), before t = 0.06[s] the source current is distorted with a THD of 19.46% due to the resonance of the input filter without active damping, then after t = 0.06[s] the source current is highly improved with a THD of 1.85% with the implementation of active damping, besides, it can be found that the source current is in phase with the source voltage, proving that unit power factor operation is achieved. From Fig. 5(b), before t = 0.06[s] without active damping it is observed that the output current presents a THD of 0.63% with an almost sinusoidal waveform and a very good tracking to the output-current reference, then after t = 0.06[s] with active damping the output current is not considerable damaged because the THD is 1.37%. From Fig. 5(c), a maximum CMV of 170[V] is observed with an apparent reduction of the CMV (almost 25%) after active damping implementation. The simulation results of M²PC strategy for the IMC are demonstrated in Fig. 6, where the output-current frequency is set to 25[Hz] and the other control parameters are the same with that in Fig. 5. From Fig. 6, it can be noted that when the output-current frequency varies, a considerable improvement of the source current, an ignorable influence on the output current and an apparent reduction of CMV are achieved at the same time with active damping, indicating stable control performances for wide variations of the output-current frequency.

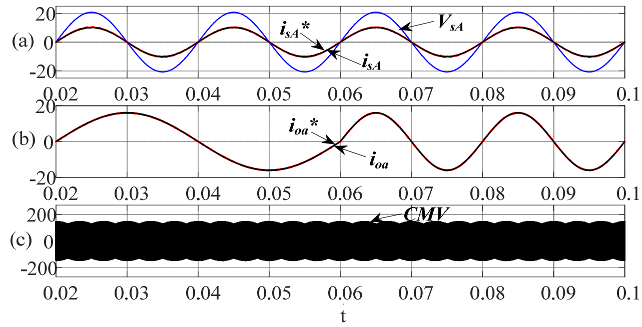

Fig. 7. Simulation results of M²PC strategy for the IMC with active damping, where output-current reference amplitude is set to 16[A]: before t = 0.06[s] output-current frequency is set to 25[Hz], after t = 0.06[s] output-current frequency is set to 50[Hz]: (a) source voltage V_{sA} / 15 [V], source-current reference i_{sA}^* [A] and source current i_{sA} [A]; (b) output-current reference i_{oa}^* [A] and output current i_{oa} [A]; (c) common-mode voltage CMV [V].

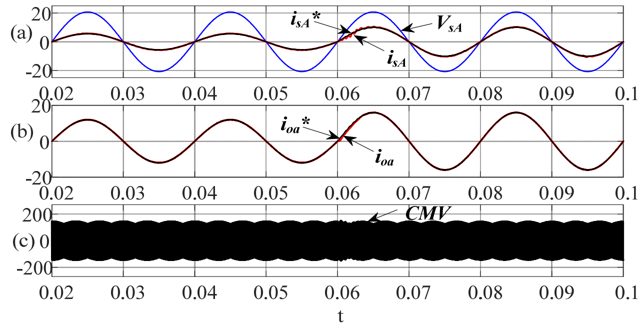

Fig. 8. Simulation results of M²PC strategy for the IMC with active damping, where output-current frequency is set to 50[Hz]: before t = 0.06[s] output-current reference amplitude is set to 12[A], after t = 0.06[s] output-current reference amplitude is set to 16[A]: (a) source voltage V_{sA} / 15 [V], source-current reference i_{sA}^*[A] and source current i_{sA}[A]; (b) output-current reference i_{oa}^*[A] and output current i_{oa} [A]; (c) CMV [V].

In order to evaluate the performance of M²PC strategy for the IMC with active damping in transient state, a step change from 25[Hz] to 50[Hz] at t = 0.06[s] is applied to output-current frequency considering both cases in Fig. 7, and a step change from 12[A] to 16[A] at t = 0.06[s] is applied to output-current reference considering both cases in Fig. 8. In Fig. 7 and Fig. 8, almost sinusoidal waveforms of the source current and output current with low THDs are obtained indicating a very good tracking to their respective references, the source current is always in phase with the source voltage with unit power factor operation, and reduced CMVs is achieved in all cases of output-current reference and output-current frequency changes. As expected, the proposed strategy demonstrates a fast dynamic response and a good performance in transient state.

VI. Conclusion

In this paper, a modulated model predictive current control of an indirect matrix converter with active damping has been validated in simulation. On the one hand, a fixed switching frequency and the optimal switching pattern lead to a better spectrum distribution of both input and output sides than traditional MPC, on the other hand, active damping improves the quality of the source currents even in the presence of a weakly damped input filter, furthermore, CMV is reduced. The research of this paper provides an effective control strategy of an indirect matrix converter with consideration of the switching frequency and pattern, input filter resonance mitigation and CMV, which makes model predictive control more competitive with respect to conventional PWM algorithms when applied to matrix converter. By approaching the control task from this different perspective, a very attractive alternative control for matrix converter has been demonstrated.

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