Alternating Sequential Model Predictive Control of Matrix Converter

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***Abstract*—Weighting factor design is one of the challenges faced by model predictive control (MPC) when multiple control objectives are to be achieved simultaneously. This paper proposes an alternating sequential MPC (ASMPC) in which the cost functions are evaluated in alternating order, avoiding the weighting factor selection and the need to determine the evaluation order for each cost function. Reduced computational burden is achieved at the same time. The proposed ASMPC has been applied to the control of a matrix converter and simulation results verify the feasibility and effectiveness of the proposed controller. The proposed ASMPC can be readily adapted and used for other power electronic converters.**

Keywords—Alternating Sequential Model Predictive Control; Model Predictive Control (MPC); Matrix Converter; Weighting Factor

I. Introduction

Thanks to simplicity in implementation, fast response, flexibility in control, capability to handle multi-control objective and system constraints, model predictive control (MPC) has been a popular research topic in power electronic converters and motor drives in recent years [1-4]. MPC is regarded by many as a competitive and promising alternative control technique to classical control strategies [5].

MPC utilizes a system model to predict the future behavior of the controlled variables. In power electronic converters, different switch states lead to the different future behavior of the controlled variable. A cost function representing the control error is used in MPC to evaluate each switch state and the one producing the least error is selected as an optimization control input for the next period. However, there are some challenges facing the MPC, mainly including complicated weighting factor design, dependent on system parameters, and intensive computation especially if there are a significant number of switch states [6]. This paper focuses on addressing the issues associated with the weighting factor.

When dealing with multiple control objectives simultaneously, weighting factors are needed to adjust the controller's attention to each control objective. In many cases, the controlled variables have different characteristics and they do not share the same unit or order of magnitude, which makes the design of weighting factors more intractable. Tunning weighting factor typically involves a heuristic process based on empirical methods, which is indeterminate and time-consuming.

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Weighting factors design guidelines for MPC in power converters and drives have been presented in [7]. However, the tuning of the weighting factor is still based on trial-and-error procedures. Some other efforts devoted to removing weighting factors need to normalize controlled quantities or convert them into equivalents [8]. It is interesting that some advanced algorithms such as artificial neural networks [9], fuzzy optimization [10], genetic algorithms [11], and particle swarm optimization [12], have been used to deal with the weighting factor issue in MPC. These advanced algorithms increase the complexity, which removes one of the advantages of MPC implementations.

Recently, sequential MPC (SMPC) has been proposed to eliminate the need for weighting factors [13]. In SMPC, cost functions corresponding to each control objective are evaluated in a sequential order. The evaluation order is determined according to the priority or relative importance of each control objective [14]. In fact, setting priority for each control objective, i.e., determining the evaluation order of cost functions, is setting the weighting factor in a different way. In addition, inappropriate evaluation orders can lead to unsatisfactory performance or abnormal operation of the controlled systems [15]. Therefore, SMPC does not, in essence, remove the weighting factors. However, SMPC is suitable for applications where the control objectives have distinctly different priorities.

An amendment to SMPC, named generalized SMPC, has been considered for induction motor drives [15]. In this proposed scheme, three switching states, rather than two, are pre-selected after evaluation of the first cost function. The evaluation order of the cost functions is not limited by priority. However, this method cannot be effectively extended to control other power electronic converters, among which a matrix converter (MC) is an example. An even-handed SMPC considering the cross error has been investigated [16]. However, cost functions need to be evaluated for all valid switch states, which causes an undesired heavy computational burden.

This paper proposes an alternating SMPC (ASMPC) scheme and the main contributions include: (1) the cost functions in the proposed ASMPC are evaluated in alternating manner, thus removing the weighting factor; (2) the pre-determined evaluation order for cost functions is not required in the proposed ASMPC since the cost functions are evaluated alternatingly; (3) the computational burden of the proposed ASMPC is reduced compared with the traditional MPC and the proposed method has been demonstrated for the control of an MC. Finally, a comparative simulation study based on MC performance has been used to compare the performances of the SMPC and the proposed ASMPC.

II. Predictive Models

Due to the advantages of no bulky energy storage devices (thus compact volume and high power density), direct AC/AC conversion, bidirectional power flow, controllable input power factor and flexibility in controlling output voltage and frequency, the MC has attracted the attention from academia and industry [17-19]. Among many controllers for MC, MPC is a simple and powerful control technique considering that most control methods for MC are complex. Predictive models are needed in MPC to predict the future behavior of the controlled variable.

An MC with input filters and a load represented as a resistive-inductive circuit is shown in Fig. 1. There are nine bidirectional semiconductor switches in an MC, giving 27 valid switch states considering the constraints to avoid short circuits at the input and open circuits at the output. The more switch states, the more computational burden in MPC. Therefore, the computational burden of MPC for MC is heavy.

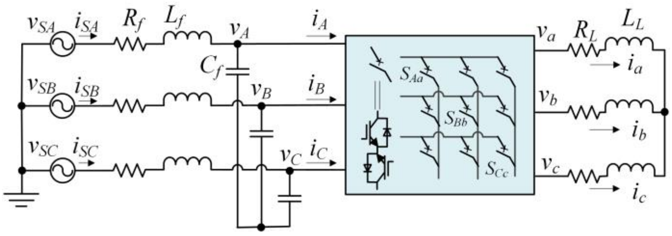

Fig. 1. MC system.

The output voltages and input currents can be obtained using the input voltages and output currents respectively together with the switch matrix, as expressed by

$$\mathbf{v}_o=\begin{bmatrix}v_a\\v_b\\v_c\end{bmatrix}=\begin{bmatrix}S_{Aa}&S_{Ba}&S_{Ca}\\S_{Ab}&S_{Bb}&S_{Cb}\\S_{Ac}&S_{Bc}&S_{Cc}\end{bmatrix}\begin{bmatrix}v_A\\v_B\\v_C\end{bmatrix}=S\begin{bmatrix}v_A\\v_B\\v_C\end{bmatrix}=S\mathbf{v}_i \tag{1}$$

$$\mathbf{i}_\mathrm{i}=\begin{bmatrix}i_A\\i_B\\i_C\end{bmatrix}=\begin{bmatrix}S_{Aa}&S_{Ab}&S_{Ac}\\S_{Ba}&S_{Bb}&S_{Bc}\\S_{Ca}&S_{Cb}&S_{Cc}\end{bmatrix}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix}=S^T\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix}=S^T\mathbf{i}_o \tag{2}$$

$$\sum_{X=A,B,C}S_{Xx}=1,(x=a,b,c) \tag{3}$$

where S (and its transpose S^T) is the switch matrix and other variables are denoted in Fig. 1. The expression (3) is applied as a constraint to exclude the switch states that can cause overvoltage at the output and overcurrent at the input.

An output current predictive model can be developed to predict the output current for implementing MPC. Due to the symmetry of the three-phase system, only a one-phase model is used for the descriptions. For the resistive-inductive load (R_L, L_L), the load model for output phase a can be represented as:

$$v_a=i_aR_L+L_L\frac{di_a}{dt} \tag{4}$$

Equation (4) is discretized using sampling time T_s,

$$i_a[k+1]=i_a[k]-\frac{R_LT_s}{L_L}i_a[k]+\frac{T_s}{L_L}v_a[k] \tag{5}$$

where $i_a[k]$ is obtained by measurement and $v_a[k]$ is calculated using (1). The predictive output current can be obtained using the discretized model (5). The predictive models for the other two output phases can be derived in the same way.

In terms of the control at the input, there are usually two common methods including source reactive power minimization (for unity source input power factor) and imposed source current regulation. In both methods, the source current needs to be predicted, thus requiring a predictive model. The input filter model has been used to develop the source current predictive model. The one-phase input filter model can be expressed as:

$$v_{SA}-i_{SA}R_f-L_f\frac{di_{SA}}{dt}=v_A \tag{6}$$

$$i_{SA}=C_f\frac{dv_A}{dt}+i_A \tag{7}$$

Equations (6) and (7) can be rewritten as the state-space model

$$\begin{bmatrix}\dot{i}_{SA}\\\dot{v}_A\end{bmatrix}=F\begin{bmatrix}i_{SA}\\v_A\end{bmatrix}+G\begin{bmatrix}v_{SA}\\i_A\end{bmatrix} \tag{8}$$

where $F=\begin{bmatrix}-R_f/L_f&-1/L_f\\1/C_f&0\end{bmatrix}$, $G=\begin{bmatrix}1/L_f&0\\0&-1/C_f\end{bmatrix}$.

The discretized model of (8) is then obtained

$$\begin{bmatrix}i_{SA}[k+1]\\v_A[k+1]\end{bmatrix}=A\begin{bmatrix}i_{SA}[k]\\v_A[k]\end{bmatrix}+B\begin{bmatrix}v_{SA}[k]\\i_A[k]\end{bmatrix} \tag{9}$$

where $A=e^{F\cdot T_s}$, $B=\int_0^{T_s}e^{F\cdot\tau}d\tau\cdot G$, $A=\begin{bmatrix}A_{11}&A_{12}\\A_{21}&A_{22}\end{bmatrix}$,

$$A_{11}=\frac{a\cdot e^{a\cdot T_s}-b\cdot e^{b\cdot T_s}}{a-b},\ A_{12}=\frac{-(e^{a\cdot T_s}-e^{b\cdot T_s})}{L_{oa}(a-b)},$$

$$A_{21}=\frac{e^{a\cdot T_s}-e^{b\cdot T_s}}{C_{ab}(a-b)},\ A_{22}=\frac{a\cdot e^{a\cdot T_s}-b\cdot e^{b\cdot T_s}}{a-b}+\frac{R_{oa}\cdot(e^{a\cdot T_s}-e^{b\cdot T_s})}{L_{oa}(a-b)},$$

$$B=\begin{bmatrix}B_{11}&B_{12}\\B_{21}&B_{22}\end{bmatrix},\ B_{11}=\frac{e^{a\cdot T_s}-e^{b\cdot T_s}}{L_{oa}(a-b)},$$

$$B_{12}=\frac{[a\cdot(e^{b\cdot T_s}-1)-b\cdot(e^{a\cdot T_s}-1)]}{(L_{oa}\cdot C_{oa}\cdot a\cdot b)\cdot(a-b)},\ B_{21}=-B_{12},$$

$$B_{22}=\frac{-e^{a\cdot T_s}+e^{b\cdot T_s}+R_{oa}\cdot[a-b-a\cdot e^{b\cdot T_s}+b\cdot e^{a\cdot T_s}]}{(L_{oa}\cdot C_{oa}\cdot a\cdot b)\cdot(a-b)},$$

and $a,b=\dfrac{-R_A/L_A\pm\sqrt{(R_A/L_A)^2-4/C_A/L_A}}{2}$.

According to (9), the source current can be predicted using:

$$i_{SA}[k+1] = A_{11}i_{SA}[k] + A_{12}v_A[k] + B_{11}v_{SA}[k] + B_{12}i_A[k] \quad (10)$$

where $i_{SA}[k]$, $v_{SA}[k]$ and $v_A[k]$ are obtained from measurement; $i_A[k]$ is calculated using (2). Similarly, the source current predictive models for the other two input phases can be obtained. The above models have been developed in the *abc* three-phase system and they can be transformed into the $\alpha\beta$ components. For source reactive power minimization, the predicted source reactive power can be computed:

$$Q[k+1] = \frac{3}{2}\left(v_{S\beta}[k+1]i_{S\alpha}[k+1] - v_{S\alpha}[k+1]i_{S\beta}[k+1]\right) \quad (11)$$

The source voltage is supplied by the grid and it rarely changes during a short sampling interval. Therefore $v_{S\alpha,\beta}[k+1]$ is approximated by $v_{S\alpha,\beta}[k]$. It is reported that the source reactive power minimization method cannot generate a sinusoidal source current waveform, especially in the case of a weak grid [20].

In the imposed source current control method, a source current reference needs to be given. According to the conclusions in [21], the reference source current amplitude can be calculated:

$$I_s = \frac{k_1V_S - \sqrt{(k_1V_S)^2 - \dfrac{4k_1R_fR_LI_o^2}{\eta}}}{2k_1R_f}, \quad k_1 = 1 - 8\pi^2 f_S^2 C_f L_f \quad (12)$$

where V_S is the source voltage amplitude; I_o is the MC output current amplitude; R_L is the load resistance; and η is the efficiency of the MC.

The phase of the reference source current can be obtained according to the source active and reactive power control requirements. Typically, a unity source input power factor is often desired at the input of an MC system. Therefore, the source current is regulated to be in phase with the source voltage. A phase-locked loop (PLL) is needed to acquire the amplitude and phase angle of the source voltage. The imposed source current control method is therefore employed in this paper for the input control of the MC.

III. SMPC and ASMPC

Cost functions are used in MPC to evaluate the influence of each switch state on the controlled variable. The cost function usually represents the control errors in different forms. The switch state that leads to a minimum value of the cost function, i.e., a minimum value of control error is selected and applied in the converter. In this paper, the control objectives are the MC output currents and source currents. Their corresponding cost functions are:

$$g_1 = \left|i_a^* - i_a[k+1]\right| + \left|i_b^* - i_b[k+1]\right| + \left|i_c^* - i_c[k+1]\right| \quad (13)$$

$$g_2 = \left|i_{SA}^* - i_{SA}[k+1]\right| + \left|i_{SB}^* - i_{SB}[k+1]\right| + \left|i_{SC}^* - i_{SC}[k+1]\right| \quad (14)$$

where i_a^*, i_b^*, i_c^* are the MC output current references and i_{SA}^*, i_{SB}^*, i_{SC}^* are the desired source currents obtained using (12) and source voltage phase angle via PLL.

In standard MPC, the two cost functions (13) and (14) are added together to form one overall cost function, i.e.,

$$g = g_1 + \lambda g_2 \quad (15)$$

where λ is the weighting factor that determines the relative priority of each control objective in the controller. Tuning the weighting factor is often a cumbersome and time-consuming process. A trade-off between control objectives is typically a result of weighting factor tuning.

In SMPC, cost functions are evaluated sequentially based on their priorities. Two candidate switch states are selected through the evaluation of the first cost function that has the higher priority. These two candidate switch states are evaluated by the second cost function and the one minimizing the second cost function is finally selected. Therefore, the complex weighting factor design process is circumvented and the computational burden is decreased [14, 22]. Nevertheless, specifying the priority for control objectives is required and it is actually setting the relative importance of each control objective in a similar way to the weighting factor in a standard MPC scheme.

Since the output current is the primary control objective, its priority is higher than the source current control. Thus, g_1 is always evaluated before g_2 in every control interval. In fact, evaluating g_2 before g_1 could result in poor control performance. It is worth mentioning that in MCs, the output control performance needs to be ensured; otherwise, the overall control of MC is inevitably affected because of the absence of the bulky energy storage system [23]. The SMPC technique is shown in Fig. 2.

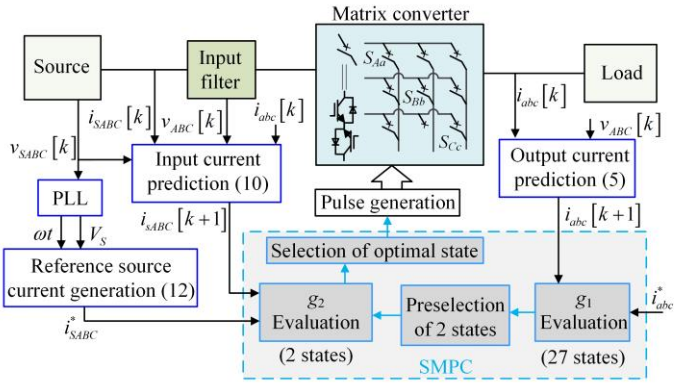

Fig. 2 Diagram of SMPC.

In the proposed ASMPC, the cost functions are evaluated in an alternating order. For example, g_1 is evaluated before g_2 in the first sampling cycle and g_2 is evaluated before g_1 in the next sampling cycle and so on. The proposed ASMPC does not need a weighting factor and there is no need to specify the priority for control objectives. In addition, the computational burden is reduced because only two switch states are evaluated in the second cost function in each control interval.

IV. Simulation Results

In order to demonstrate the effectiveness of the proposed ASMPC, simulation models were built in MATLAB/Simulink for a comparative study. The simulation parameters are tabulated in Table I.

Comparative simulation results of output currents and source currents are shown in Figs. 3 and 4, respectively.

SMPC1 represents the SMPC scheme, with g_1 being evaluated before g_2 (output current control has a higher priority). SMPC2 stands for the scheme with g_2 being evaluated before g_1(source current control has a higher priority). ASMPC denotes the proposed ASMPC strategy.

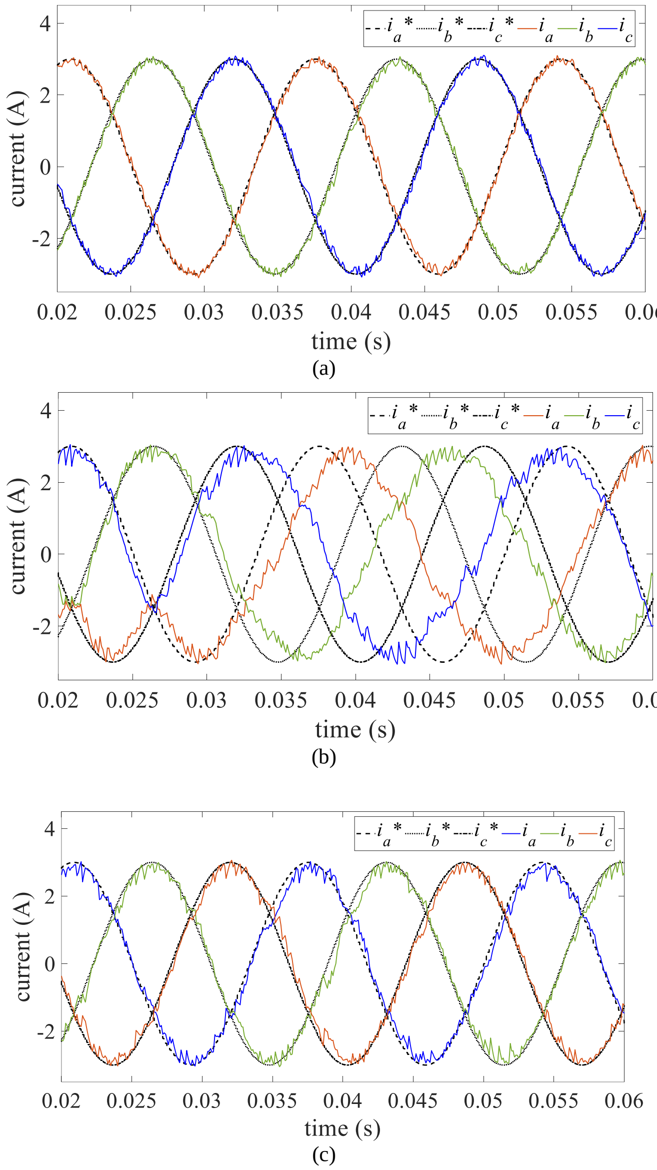

Fig. 3. Simulation waveforms of output currents: (a) SMPC1, (b) SMPC2, (c) ASMPC.

As shown in Fig. 3(a), SMPC1 can effectively control the output currents to follow the desired reference currents because the output currents control is given higher priority and the corresponding cost function is evaluated first. However, SMPC2 is no longer effective in regulating the output currents due to the lower priority assigned, as shown in Fig. 3(b). As shown in Fig. 3(c), a relatively satisfactory control performance of output current control is obtained by the proposed ASMPC. The output current control performance is compromised because the two control objectives are equally treated by means of alternating evaluation of their cost functions.

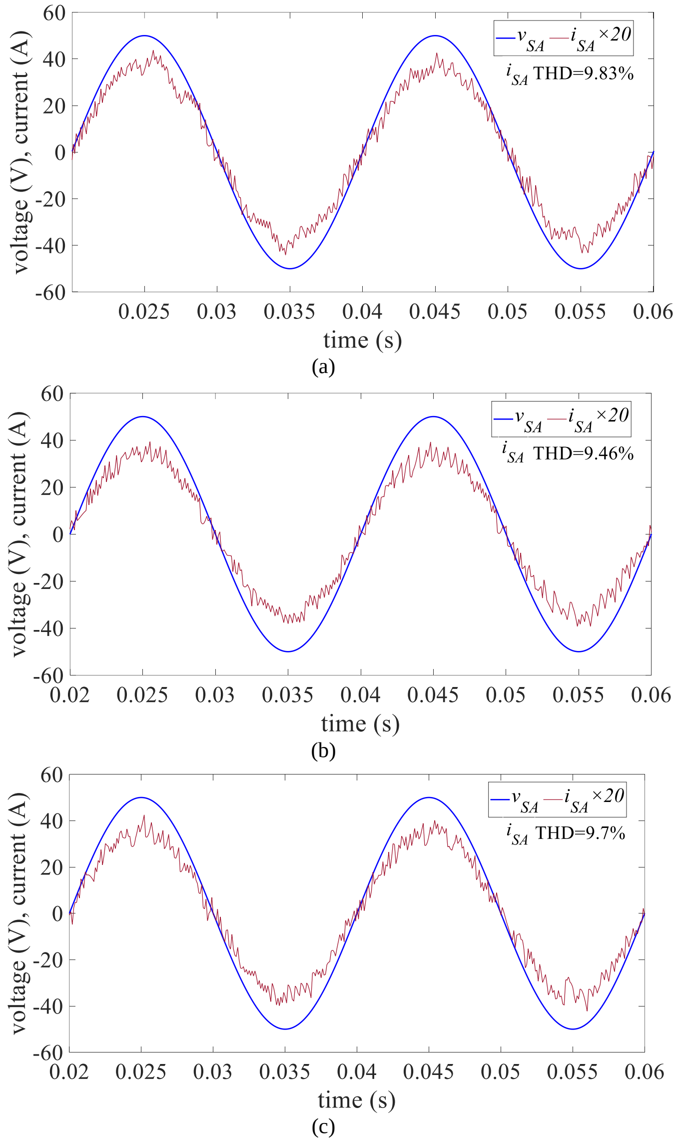

Fig. 4. Simulation waveforms of source *A*-phase voltage and current: (a) SMPC1, (b) SMPC2, (c) ASMPC.

The source current results are shown in Fig. 4. In general, SMPC1, SMPC2 and ASMPC all present similar and satisfactory performance in terms of source current control. The values of total harmonic distortion (THD) of the source currents are shown in the figure. Since the source current control has lower priority in SMPC1, its source current control shown in Fig. 4(a) is the least satisfactory among the three methods and this is confirmed by the simulation results. SMPC2 performs better in source current control as a result of a higher priority. Similar to output current control, the proposed ASMPC gives moderate performance regarding the source current control, as shown in Fig. 4(c).

TABLE 1. SIMULATION PARAMETERS.

v_S [V$_{pk\text{-}pk}$]	f_S [Hz]	L_f [mH]	C_f [μF]	R_f [Ω]	R_L [Ω]	L_L [mH]	f_o [Hz]	I_o^* [A]	T_s [μs]
100	50	6.8	30	0.5	10	14	60	3	100

In order to test the transient performance of the proposed ASMPC controller, the reference output current amplitude is changed from 3A to 2A at 0.03s, and the source current is controlled to lag the source voltage by 30° at 0.05s. The simulation results are shown in Fig. 5. As shown in Fig. 5(a), the proposed ASMPC can effectively regulate the output currents to track the references. Meanwhile, the source current can be controlled to be in phase with the source voltage realizing a unity power factor, as seen in Fig. 5(b). A lagging or leading power factor can also be achieved.

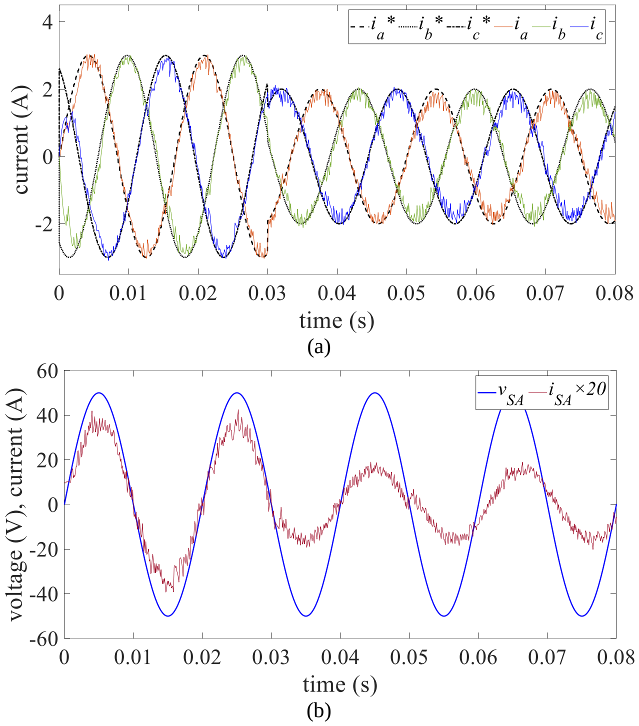

Fig. 5. Simulation results of ASMPC in transients: (a)output currents, (b) source *A*-phase voltage and current.

The output currents control performance is compromised because the output current control and source current control are treated equally in the proposed ASMPC, whereas the output current control is supposed to be the primary control goal. When there are more control objectives, the output current can be assigned a higher priority for better performance, while the other control objectives can be accomplished with the proposed ASMPC.

The proposed ASMPC can also retain the benefit of the reduced computational burden like SMPC because only-preselected switch states are evaluated in the following step. The reduced computational burden is beneficial for further improvement of the controller and practical implementation, particularly in MC considering its high number of switch states.

V. Conclusions

SMPC has been recently proposed to address the weighting factor issue in traditional MPC. However, specifying a priority for control objectives is necessary and inappropriate priority order could result in a degraded or even unsatisfactory performance in some cases. This paper proposes the ASMPC for matrix converters. Neither weighting factor nor assigning priority is required in the proposed ASMPC technique, and the low computational burden is retained since only the pre-selected switches are evaluated in the following step. The proposed ASMPC is particularly suitable for applications where control objectives are equally important and a compromising solution is required. For the system which has a primary or more important control objective that needs to be realized to ensure proper operation of the system, the primary control objective can be assigned a higher priority and its cost function is always evaluated first, whilst the cost functions of remaining control goals are evaluated in an alternating order adopting the proposed ASMPC. The proposed ASMPC can also be readily extended for controlling other power electronic converters.

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