Sequential Model Predictive Control of Direct Matrix Converter without Weighting Factors

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***Abstract*—The direct matrix converter (MC) is a promising converter that performs direct AC-to-AC conversion. Model predictive control (MPC) is a simple and powerful control strategy for power electronic converters including the MC. However, weighting factor design and heavy computational burden impose significant challenges for this control strategy. This paper investigates the sequential MPC (SMPC) for a three-phase direct MC. In this control strategy, each control objective has an individual cost function and these cost functions are evaluated sequentially based on priority. The complex weighting factor design process is not required and the computational burden can be reduced. In addition, specifying the priority for control objectives can be achieved. A comparative simulation study with standard MPC is carried out in Matlab/Simulink. Control performance is compared to the standard MPC and found to be comparable. Simulation results verify the effectiveness of the proposed strategy.**

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

I. INTRODUCTION

The direct matrix converter (MC) carries out direct AC-to-AC power conversion, and it does not require any bulky energy storage devices. A three-phase direct MC is shown in Fig. 1. This converter provides many benefits including bidirectional power flow, controllable input power factor, compact volume and higher power density [1][2]. Therefore, MCs have attracted research interest and have been investigated and proposed for several application areas. Some manufacturers such as Yaskawa and Fuji have commercialized some MC products and modules. Table I summarizes the details of some of these MC products. As seen in this table, the maximum voltage and power ratings have reached 6.6 kV and 6 MVA, these are for the Yaskawa MX1S series. The main application area of these products is industrial motor drives.

In the literature, many control methods have been investigated for MCs. These mainly include Venturini method [3][4], space vector modulation [5][6], direct torque control [7][8], hysteresis-band control [9][10] and model predictive control (MPC) [11]-[13]. Table II summarizes the performance comparison of these common control methods. Among these controllers, MPC is regarded as a popular and promising control tool in power converters and machine drives because of its simplicity, flexibility in integrating the system constraint and potential to be applied in many areas.

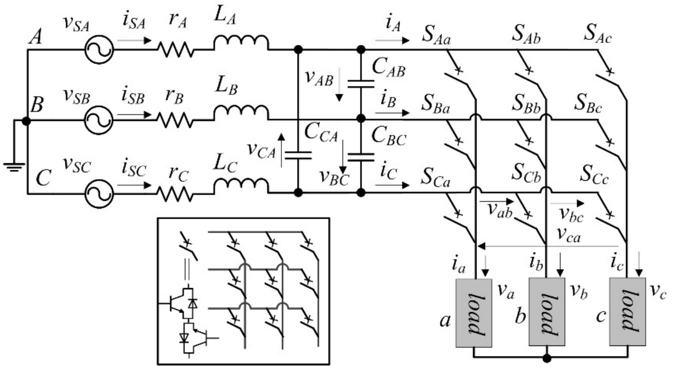

Fig. 1. Three-phase direct MC circuit.

MPC explicitly incorporates control objectives and system constraints in a cost function. All valid switch states of a converter are evaluated in this cost function to optimize the selection of switch states. The higher number of switch states results in the heavier computational burden. MPC has been investigated for most power electronic converters [14]-[17]. However, there are some drawbacks in MPC and these include complicated weighting factor design and heavy computational burden. The situation is aggravated if more control objectives need to be achieved or more switch states need to be evaluated.

The weighting factor is usually obtained using empirical methods via a trial-and-error process which is complex and time-consuming. Some research efforts have been devoted to addressing the weighting factor issues. In [18], guidelines for designing weighting factors for power converters were presented. Empirical processes are still involved in those guidelines. In [19], a multi-objective ranking-based MPC was proposed in order to regulate the torque and flux of an induction motor. Weighting factor design was avoided; however, all control objectives are treated as equal, which compromises the control. In addition, all switch states are evaluated in each cost function, resulting in heavy

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TABLE I. INFORMATION OF SOME MC PRODUCTS AND MODULES.

Manufacturer	Product/Model	Max. Voltage	Max. Power	Target Application	Other Information/Feature
Yaskawa	FSDrive-MX1S	6.6 kV	6 MVA	motor drive	energy-saving
Yaskawa	U1000	480 V	800 HP	motor drive	full regeneration, ultra-low harmonics
Yaskawa	AC7	480 V	250 HP	motor drive	legacy product
Yaskawa	Z1000U	480 V	350 HP	HVAC applications	low input distortion
Eupec	ECONOMAC FM35R12KE3ENG	1200 V	42 kVA	unspecified	Module
Fuji	FRENIC-Mx	400 V	45 kW	general industrial machines	best suitable for elevators and cranes

TABLE II. PERFORMANCE COMPARISON OF SOME MC CONTROL TECHNIQUES.

	Venturini Control	Space Vector Modulation	Direct Torque Control	Predictive Control	Hysteresis Control
Complexity	low	high	medium	low	very low
Sampling Frequency	very low	low	very high	high	high
Switching Frequency	very low	low	high	high	High
Dynamic Response	good	good	Fast	very fast	very fast
Application Range	narrow	wide	Narrow	very wide	medium

computational burden. Many other methods for avoiding weighting factors either require the conversion of the regulated variables into equivalent quantities or involve other algorithms [20]-[23]. These are undesirable because the control system complexity is increased.

This paper investigates a possible solution, i.e., the sequential MPC (SMPC), for a three-phase direct MC. In this control strategy, the complex weighting factor design process is avoided, and thus the computational burden is reduced. The contributions of this paper include: (i) an SMPC strategy is proposed and this method is investigated for a three-phase direct MC; the regulation of different control objectives can be achieved, avoiding complex design of weighting factors; (ii) with the proposed control strategy, the cost functions corresponding to control objectives are evaluated individually and sequentially, in this way, the computational burden is reduced since only the pre-selected switch states are evaluated in the subsequent cost functions; and (iii) priority of control objectives can be specified with the proposed strategy.

A comparative simulation study is carried out to compare the performance of the proposed controller with the conventional MPC. Similar performance can be achieved, while the reduced computational burden enables further improvement of performance in the proposed strategy. Simulation results are presented to verify the proposed SMPC.

II. PREDICTION MODELS OF MC AND LOAD

There are nine bidirectional semiconductor switches in a three-phase direct MC, as shown in Fig. 1. These nine switches allow 27 valid switch states that need to be evaluated in the cost function of the MPC. The high number of switch states can lead to the heavy computational burden.

The semiconductor switches in an MC are arranged in the form of a 3×3 matrix. The relationship between the inputs and outputs of the MC can be established as

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

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

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

where S (transpose S^{T}) is the switch matrix and $v_{A,B,C}$ are the output phase voltages. Other variables are denoted in Fig. 1. The constraint (3) is used to exclude the invalid switch states that can cause detrimental overvoltage and overcurrent.

In MPC, system models are employed to predict the targeted variables. In order to regulate the MC output current, an output model needs to be developed. For an inductive-resistive load (R_a, L_a), the output model can be represented as

$$v_a = i_a R_a + L_a \frac{di_a}{dt} \tag{4}$$

Here the variables are defined in the Fig. 1. It is sufficient to consider a single-phase model due to the symmetry of the three-phase system. From (4), the discretized model to for output phase a is obtained

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

Here T_s is the sampling time. The discretized model in (5) is used to predict future behavior of the load current i_a. $i_a[k]$ is measured using a current sensor and $v_a[k]$ is calculated using (1). Another control objective considered in this work is the input power factor. For this control objective, the input filter is modeled as

$$v_{SA} - i_{SA} \cdot R_A - L_A \frac{di_{SA}}{dt} = v_A \quad (6), \qquad i_{SA} = C_A \frac{dv_A}{dt} + i_A \quad (7)$$

Here C_A represents the equivalent capacitance of C_{AB} in star connection. From (6) and (7), the discretized input filter model can be developed in state-space as follows

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

$$F = \begin{bmatrix} -R_A / L_A & -1/L_A \\ 1/C_A & 0 \end{bmatrix}, \qquad G = \begin{bmatrix} 1/L_A & 0 \\ 0 & -1/C_A \end{bmatrix} \tag{8}$$

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

$$A = e^{F \cdot T_s}, \qquad B = \int_0^{T_s} e^{F \cdot \tau} d\tau \cdot G \tag{9}$$

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \; A_{11} = \frac{a \cdot e^{a \cdot T_s} - b \cdot e^{b \cdot T_s}}{a-b},$$

$$A_{12} = \frac{-(e^{a \cdot T_s} - e^{b \cdot T_s})}{L_{oa}(a-b)}, \qquad A_{21} = \frac{e^{a \cdot T_s} - e^{b \cdot T_s}}{C_{ab}(a-b)},$$

$$A_{22} = \frac{a \cdot e^{a \cdot T_s} - b \cdot e^{b \cdot T_s}}{a-b} + \frac{R_{oa} \cdot (e^{a \cdot T_s} - e^{b \cdot T_s})}{L_{oa}(a-b)} \tag{10}$$

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

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

$$B_{22} = \frac{-e^{a \cdot T_s} + e^{b \cdot T_s} + R_{oa} \cdot [a - b - a \cdot e^{b \cdot T_s} + b \cdot e^{a \cdot T_s}]}{(L_{oa} \cdot C_{oa} \cdot a \cdot b) \cdot (a-b)} \tag{11}$$

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

Therefore, the discretized model to predict i_{SA} is

$$\begin{aligned} i_{SA}[k+1] = {} & A_{11} \cdot i_{SA}[k] + A_{12} \cdot v_A[k] \\ & + B_{11} \cdot v_{SA}[k] + B_{12} \cdot i_A[k] \end{aligned} \tag{12}$$

Here $i_{SA}[k]$, $v_{SA}[k]$ and $v_A[k]$ are measured using sensors while $i_A[k]$ is calculated using (2). In order to compute the input reactive power, the three-phase variables are converted into α-β-γ components using

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_\gamma \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{13}$$

where $i_{a,b,c}$ are the three-phase currents in the abc system and $i_{\alpha,\beta,\gamma}$ are the currents in the $\alpha\beta\gamma$ system. The input reactive power is computed from

$$Q[k+1] = \frac{3}{2} \begin{pmatrix} v_{SA-\beta}[k+1] i_{SA-\alpha}[k+1] \\ -v_{SA-\alpha}[k+1] i_{SA-\beta}[k+1] \end{pmatrix} \tag{14}$$

The supply voltage is considered stable and it barely changes during a short sampling cycle. Therefore $v_{SA-\alpha,\beta}[k+1] = v_{SA-\alpha,\beta}[k]$ holds.

III. SYSTEMATIC DESCRIPTIONS OF SMPC

The system diagram of the proposed SMPC is illustrated in Fig. 2. As shown in the diagram, the proposed SMPC can be carried out in the following steps:

Step 1: Determine n control objectives or variables that need to be regulated. Sort these control objectives in terms of priority (from high to low: 1st, 2nd ⋯ nth). Define an individual cost function (g_1 to g_n) for each control objective. The cost functions will be evaluated in sequential order as explained below.

Step 2: Evaluate all m available switch states (switch actions) and select n most suitable switch states that render the minimum values of g_1 for regulating the first control objective.

Step 3: Evaluate the n switch states selected in the previous step and select n-1 most suitable switch states that render the minimum values of g_2 for regulating the second control objective.

Step x: Evaluate the n-x+3 switch states selected in the previous step and select n-x+2 most suitable switch states that render the minimum values of g_3 for regulating the (x-1)th control objective.

Step n+1: Evaluate the two switch states selected in the previous step and select the most suitable switch states that render the minimum values of g_n for regulating the nth control objective.

In this work, there are two control objectives (n = 2), i.e., the load currents and input power factor considered in SMPC for MC. The main control objective is the regulation of the load currents, so it has the highest priority. There are 27 (m = 27) allowable switch states in total in the MC. The cost

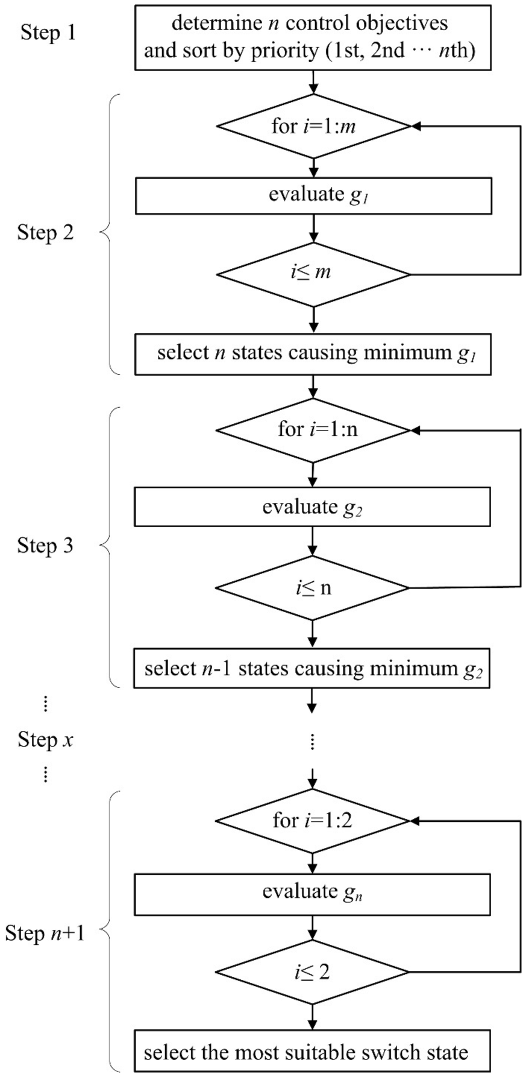


Fig. 2. System diagram of the SMPC strategy.

functions for optimizing the selection of switch states for load currents and input power factor are individually defined in

$$g_1 = \left|i_a^* - i_a[k+1]\right| + \left|i_b^* - i_b[k+1]\right| + \left|i_c^* - i_c[k+1]\right| \tag{15}$$

$$g_2 = \left|Q^* - Q[k+1]\right| \tag{16}$$

Here no weighting factors need to be designed for the proposed SMPC. However, in the traditional MPC, the cost function is

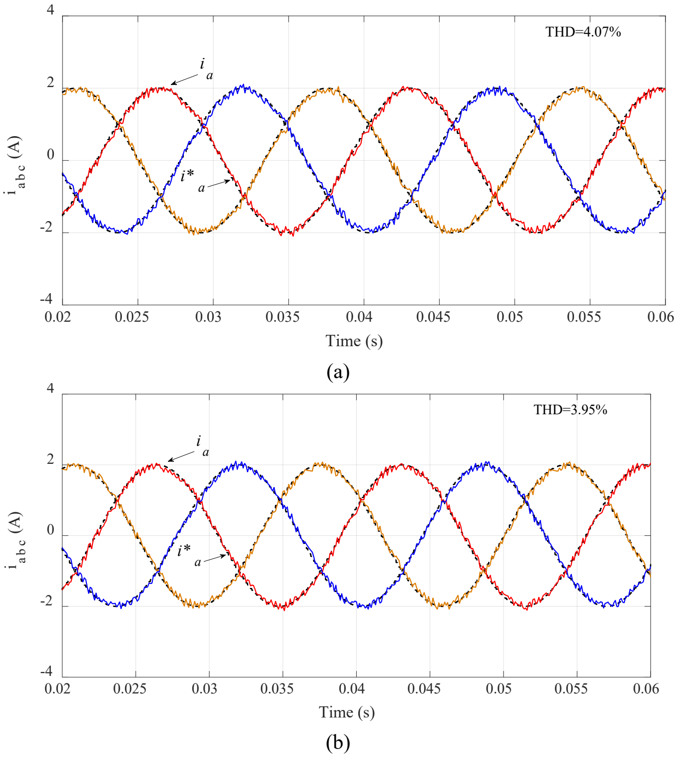
$$g = g_1 + \lambda g_2 \tag{17}$$

where λ is the weighting factor which is usually obtained by time-consuming empirical methods through a complex process. The weighting factor specifies the relative importance of the control objective in traditional MPC methods.

IV. SIMULATION RESULTS

In order to verify the effectiveness of the proposed controller, comparative simulation tests were carried out in Matlab/Simulink. The system and controller parameters are tabulated in Table III. The amplitude of the reference load current was set to 2 A. The reactive power reference was set to zero because a unity power factor is desired. In the traditional MPC, a weighting factor of λ = 0.0008 was used, which was obtained by a lengthy trial-and-error process. In the simulation results, the black dashed lines represent the current reference waveform (e.g., i_a^*).

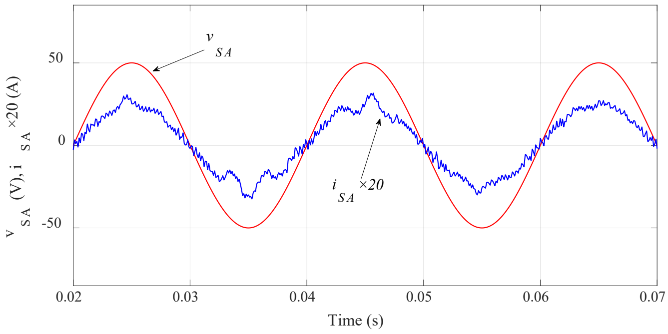
Fig. 3 compares the standard MPC and the proposed SMPC in terms of the output current regulation. As observed in this figure, the performance of the proposed SMPC is very similar to the standard MPC. The total harmonic distortion (THD) in the standard MPC is 4.07 % while it is 3.95 % in the proposed SMPC. Fig. 4 compares the input power factor regulation of two methods. Both methods can regulate the input current to be in phase with the input voltage, resulting in unity power factor. As concluded from these results, the proposed SMPC exhibits comparable results to the standard MPC. However, the complex weighting factor design is not required in the proposed SMPC.



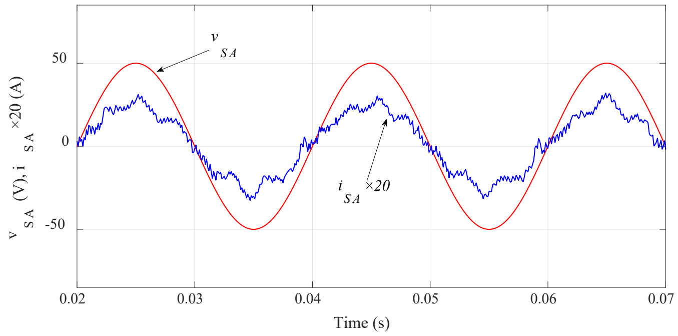
(a)

(b)

Fig. 3. Simulation results of controlled load currents by (a) MPC, and (b) proposed SMPC.

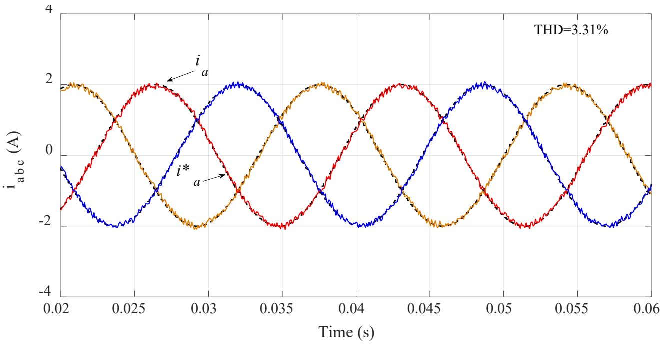


(a)

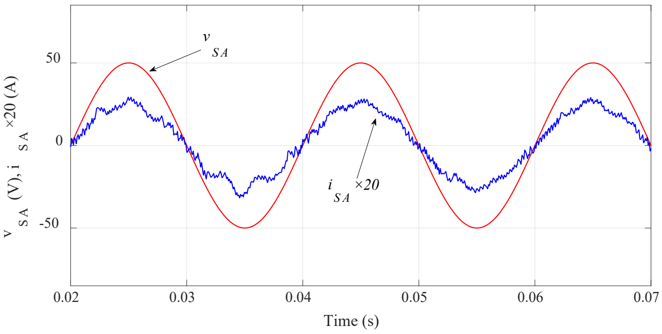


(b)

Fig. 4. Simulation results of controlled input power factor by (a) MPC, and (b) proposed SMPC.



(a)



(b)

Fig. 5. Simulation results of (a) controlled currents, and (b) input power factor by the proposed SMPC when $T_s = 80$ µs.

The proposed SMPC reduces the computational burden and can potentially further improve the performance. Compared with the standard MPC, the computation burden is reduced because only the pre-selected switch states are evaluated in the second and subsequent sequential cost functions. In addition, the prediction model computation for the following cost functions is also reduced. These further improve the performance by increasing the sampling frequency of the algorithm. However, this is difficult to achieve in the standard MPC because all switch states are evaluated in all cost functions; otherwise some pre-selection technique has to be applied. In order to verify this benefit of the proposed SMPC, the sampling time was reduced to 80 µs, which should comply with the future experimental implementation. The simulation results for the proposed SMPC with T_s = 80 µs are shown in Fig. 5. The regulated output current is improved in terms of the waveform and THD (3.31 %) and the input waveform is also improved.

Table IV compares and summarizes the performance of SMPC and MPC. The proposed SMPC performs similarly to the standard MPC in terms of the evaluated performance with a slightly lower average switching frequency. These simulation results demonstrate the effectiveness of the proposed SMPC.

TABLE III. SYSTEM AND CONTROLLER PARAMETERS.

v_s [$V_{pk\text{-}pk}$]	f_s [Hz]	L_A [mH]	C_A [µF]	R_A [Ω]	R_L [Ω]	L_L [mH]	f_o [Hz]	Q^* [VAr]	T_s [µs]
100	50	6.8	10	0.5	15	14	60	0	100

TABLE IV. COMPARATIVE PERFORMANCE EVALUATION OF SMPC AND MPC.

	T_s	Avg. Switching Frequency	Weighting Factor	Output Current THD	Input Power Factor
MPC	100 µs	2.038 kHz	0.0008	4.07%	0.997
SMPC1	100 µs	1.89 kHz	none	3.95%	0.996
SMPC2	80 µs	2.37 kHz	none	3.31%	0.997

V. CONCLUSIONS

An SMPC is proposed for a three-phase direct MC in this paper. In the proposed SMPC strategy, each control objective has an individual cost function. These cost functions are evaluated in sequential order according to the pre-determined priority. Weighting factor design is avoided in the proposed strategy, so the controller design process is simplified. In addition, the computational burden is reduced because only the pre-determined switch states are evaluated in the subsequent cost functions. The computation of prediction models for the following cost functions is reduced as well. These enable further enhancement of the control performance by increasing the sampling frequency. The comparative results to the standard MPC are achieved. The effectiveness of the proposed controller is verified by the simulation results. The proposed controller becomes more beneficial when more control objectives and more switch states are considered. The proposed SMPC can be readily extended to other converters and systems. The experimental work will be carried out to support the simulation results and verify the effectiveness of the proposed SMPC.

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