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Research Article

Analysis of Model Predictive Current Control for Voltage Source Inverter

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Abstract: Model predictive control has become a promising control technology in power converter, because of the good dynamic response and accurate current tracking capability. This study mainly analyzes and verifies the Model Predictive Current control (MPC) of a three-phase voltage sources converter. The MPC controller predicts the behavior of the converter for each possible voltage vector on each sampling interval. And a cost function is used to evaluate the voltage vector for the next sampling interval based the predicted load behavior. According to the assessment, an optimal voltage vector is selected and the corresponding switching state is applied to the converter during the next sampling interval. Finally, simulation and experimental results are demonstrated to validate the steady-state and dynamic performance of the proposed system.

Keywords: Model predictive control, predictive control, Voltage Source Inverter (VSI)

INTRODUCTION

Recently, Model Predictive Current control (MPC) has been paid more attention for power converter and AC drive because of its simplicity, good dynamic performance, strong current tracking ability, less sensitivity to the system model in Jos *et al*. (2007), Cortes *et al*. (2008) and Kouro *et al*. (2009). MPC will predict the future behavior of the variables in time frame considering the model of the system. All the predictions are valued based on a cost function and that minimizes the cost function is the optimal control sequence.

Nowadays, MPC has been applied to various types of converters. MPC has been used to control a voltage source inverter (Jos *et al*., 2007) electric drives (Cortes *et al*., 2008). And it is also employed in three-level NPC inverter (Vargas *et al*., 2007), an asymmetric cascaded H-bridge inverters in Perez *et al*. (2008) and a 3-phase cascaded H-bridge inverter in Cortés *et al*. (2010). Considering all the switching states of a converter, it is difficult to reach a very high switching frequency in a standard controller if all of them are calculated. Then some optimal methods are presented to reduce the amount of calculation for general MPC. Switching frequency reduction is applied to a motor driver (Preindl *et al*., 2011). A method of variable sampling time finite control for MPC is employed in a grid-connected inverter (Hoffmann *et al*., 2012). Also, a fast-predictive controller is proposed for neutral-point-clamped multilevel converter (Barros *et al*., 2013).

In this study, a simplified predictive current control technique is applied to a voltage source inverter with MPC controller considering the optimal method of selecting the voltage vector. This method is realized by selecting the adjacent levels. The method is validated by the simulation and experimental results in a three-phase voltage source inverter.

MODELING OF THE THREE-PHASE INVERTER

Model of the converter: Figure 1 shows the configuration of a three-phase voltage source inverter with MPC controller. U_{dc} is DC link voltage which is connected with capacitor C_{dc}. v_{aN}, v_{bN} and v_{cN} are respective three-phase invert output voltage. v_{ON}, v_{ON} and v_{ON} are respective error of neutral point to grand voltage. i_a, i_b and i_c are the load current associated to the load. R is the load resistor and L is the inductor without considering equivalent series resistor. In Fig. 1, the model of the converter in static *abc* reference frame can be written as:

$$\begin{cases} L\frac{di_a}{dt} + Ri_a = u_{aN} - u_{ON} \\ L\frac{di_b}{dt} + Ri_b = u_{bN} - u_{ON} \\ L\frac{di_c}{dt} + Ri_c = u_{cN} - u_{ON} \end{cases} \quad (1)$$

where, the output voltage v_{xN} ($x = a, b, c$) of inverter are determined by the switching function of S_x ($x = a, b, c$), which can be derived as:

$$\begin{cases} u_{aN} = u_{dc} s_a \\ u_{bN} = u_{dc} s_b \\ u_{cN} = u_{dc} s_c \end{cases} \quad (2)$$

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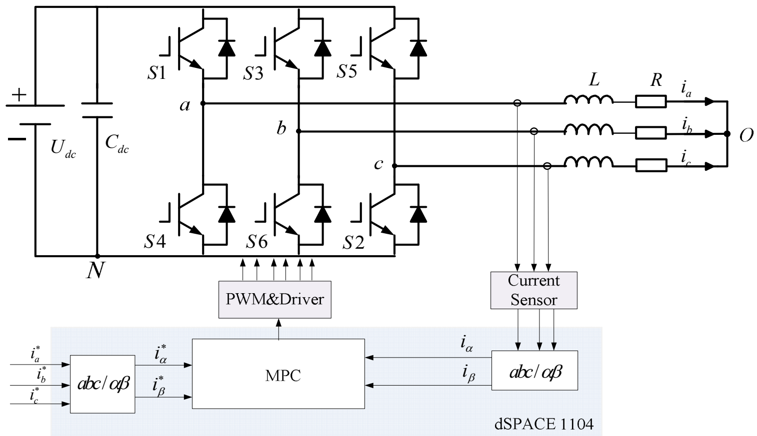

Fig. 1: Three-phase voltage source inverter with MPC controller

The switching states of the inverter are determined by the gating signals S_a, S_b and S_c as follows:

$$S_a = \begin{cases} 1, & \text{If } S1 \text{ on and } S4 \text{ off} \\ 0, & \text{If } S1 \text{ off and } S4 \text{ on} \end{cases} \tag{3}$$

$$S_b = \begin{cases} 1, & \text{If } S3 \text{ on and } S6 \text{ off} \\ 0, & \text{If } S3 \text{ off and } S6 \text{ on} \end{cases} \tag{4}$$

$$S_c = \begin{cases} 1, & \text{If } S5 \text{ on and } S2 \text{ off} \\ 0, & \text{If } S5 \text{ off and } S2 \text{ on} \end{cases} \tag{5}$$

In the stationary *abc* reference frame and for a balanced three phase system, the sum of the load current is equal to zero, which is written as:

$$i_a + i_b + i_c = 0 \tag{6}$$

By replacing (4) and (2) in (1):

$$u_{ON} = \frac{u_{dc}}{3}(s_a + s_b + s_c) \tag{7}$$

Then (7) and (2) are substituted in (1):

$$\begin{cases} L\dfrac{di_a}{dt} = \dfrac{u_{dc}}{3}(2s_a - s_b - s_c) - Ri_a \\ L\dfrac{di_b}{dt} = \dfrac{u_{dc}}{3}(2s_b - s_a - s_c) - Ri_b \\ L\dfrac{di_c}{dt} = \dfrac{u_{dc}}{3}(2s_c - s_a - s_b) - Ri_c \end{cases} \tag{8}$$

From (7), it can be found that there are six basic none zero output voltages and two zero output voltage vectors available for controlling the load current. The change in load current depends on the choice of output voltage vector. And (7) can derive as:

$$\begin{cases} L\dfrac{di_a}{dt} = v_a - Ri_a \\ L\dfrac{di_b}{dt} = v_b - Ri_b \\ L\dfrac{di_c}{dt} = v_c - Ri_c \end{cases} \tag{9}$$

where,

$$\begin{cases} v_a = \dfrac{u_{dc}}{3}(2s_a - s_b - s_c) \\ v_b = \dfrac{u_{dc}}{3}(2s_b - s_a - s_c) \\ v_c = \dfrac{u_{dc}}{3}(2s_c - s_a - s_b) \end{cases} \tag{10}$$

The load current vector can be expressed in the stationary reference frame $\alpha\beta$ as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{3s/2s} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = C_{3s/2s} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{12}$$

where, $C_{3s/2s}$ is Clarke matrix, which is defined as:

$$C_{3s/2s} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{13}$$

By replacing (12) and (13) in (9):

$$\begin{cases} L\dfrac{di_\alpha}{dt} = v_\alpha - Ri_\alpha \\ L\dfrac{di_\beta}{dt} = v_\beta - Ri_\beta \end{cases} \tag{14}$$

And (13) can be simplified as:

$$L\frac{d\mathbf{i}}{dt} = \mathbf{v} - R\mathbf{i} \tag{15}$$

where,
R = The load resistor
L = The load inductor

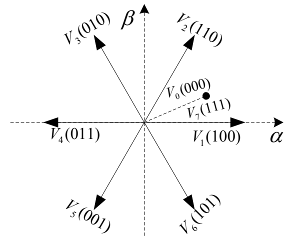

Fig. 2: Possible voltage vectors of the VSI

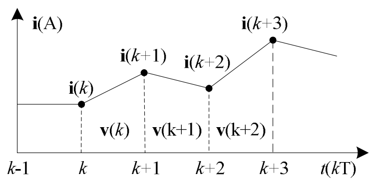

Fig. 3: Predictive load current

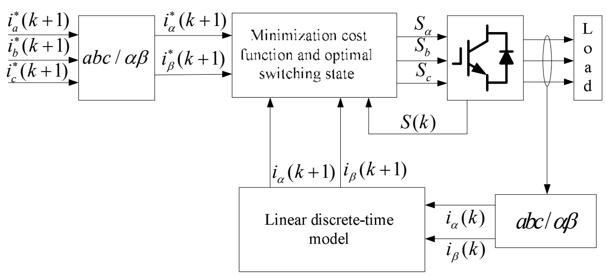

Fig. 3: MPC block diagram

v = The voltage vector of the inverter in the stationary reference frame $\alpha\beta$
i = The load current vector in the stationary reference frame $\alpha\beta$

From (14), load current vector i can be controlled by selecting the proper output voltage vector v. There are eight possible switching states and consequently six basic none zero output voltages and two zero output voltage vectors available to control the load current (Fig. 2). The change in load current depends on the choice of output voltage vector. For the seven basic voltage vectors we obtain seven possible values of change in output current:

Discrete-time model of the system: Assuming the inductor is linear and sampling time T_s is short enough, a discrete-time model of the system can be used to predict the load current in the next sampling interval (14), considering the possible output voltage vectors and measured currents at a sampling instant. In Fig. 3, during the k^{th} sampling interval, the $d\mathbf{i}/dt$ of load current can be simplified as:

$$\frac{d\mathbf{i}}{dt} \approx \frac{\mathbf{i}(k+1)-\mathbf{i}(k)}{T_s} \tag{16}$$

And replacing (15) in (14), the future load current vector can be determined by:

$$\mathbf{i}(k+1) = \frac{1}{RT_s+L}\left[L\mathbf{i}(k)+T_s\mathbf{v}(k)\right] = \frac{1}{T_s/\tau+1}\left[\mathbf{i}(k)+\frac{T_s}{L}\mathbf{v}(k)\right] \tag{17}$$

where, i (k+1) is the predictive value of load current at the time k+1. i (k) is the measured value of load current at time k. And v (k) is the selected voltage vector during sampling time interval of k+1. τ (L/R) is the time constant of the load. The term of T_s/τ can be neglected of the time constant τ is much larger than the sampling time interval T_s.

There are seven possible output voltage vectors, which mean that there are possible seven different load current vectors for future as the measured current i (k). Then we can use a selected voltage vector to estimate the future behavior of the system.

DESIGN OF MODEL PREDICTIVE CURRENT CONTROL

Configuration of MPC: The MPC controller predicts the behavior of the converter for finite possible voltage vector on each sampling interval (Kouro *et al*., 2009). And a cost function is used to evaluate the voltage vector for the next sampling interval based the predicted load behavior. The optimal switching state is selected and applied to the converter during the next sampling interval which minimizes the cost function. The MPC block diagram is shown in Fig. 3.

Cost function: The error between the reference current and the output current at the next sampling instant can be expressed as follows (Jos *et al*., 2007; Cortes *et al*., 2008; Kouro *et al*., 2009):

$$g=\left|\mathbf{i}^*(k+1)-\mathbf{i}(k+1)\right| \tag{18}$$

where, i*(k+1) the reference is current vector and I (k+1) is predictive load current vector. And the reference current i*(k+1) could be supposed equal to the i*(k) in only one sampling step. Furthermore, (17) can be derived in orthogonal coordinates as follow:

$$g_{\alpha\beta}=\left|i_\alpha^*(k)-i_\alpha(k+1)\right|+\left|i_\beta^*(k)-i_\beta(k+1)\right| \tag{19}$$

where, $i_\alpha(k+1)$ and $i_\beta(k+1)$ are the real and imaginary parts of the predicted current vector and i_α*(k), i_β* are the real and imaginary parts of the reference current vector respectively.

Then switching state is applied at next sampling instant, which is determined by the optimal voltage vector minimizing the current error.

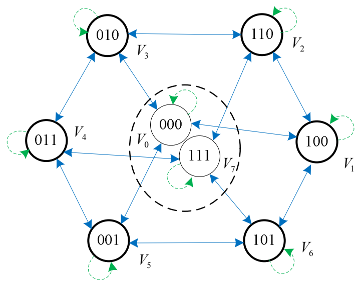

Fig. 4: Voltage vector considering adjustment (Preindl *et al*., 2011)

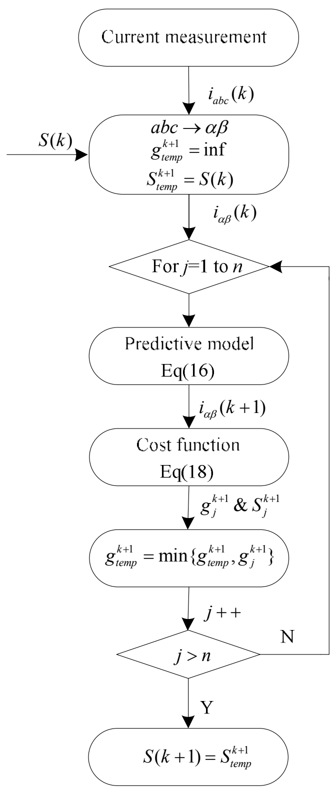

Fig. 5: Flow diagram of the MPC algorithm

Voltage vector adjustment: To finding the optimal switching state, calculation of each one cost function for different voltage vector should be made. It means that there are seven possible current errors prediction, which needs much time cost, since there are seven different voltage vectors. The large amount of calculation could not be finished in one sampling interval if it is not long enough.

A possibility, which reduces the amount of calculations, is proposed to for a VSI converter topology (Preindl *et al*., 2011). Instead of considering all the possible voltage vectors, the simplified MPC just needs a subset of all available voltage vectors for optimal vector selection shown in Fig. 4. The criteria of selecting voltage vector allow only one switching transition at maximum in all of switching function S_x. Therefore four possible voltage vectors have to be considered in each sampling time instant for the current prediction and cost function evaluation. In this study, the vector V_7 is neglected. Thus seven possible switching states should be considered for the zero vectors.

MPC algorithm: Flow diagram of the MPC algorithm is shown in Fig. 5. The output currents are measured by A/D converter at a sampling instant. The currents i_{abc} in stationary reference frame *abc* frame are transformed into $i_{\alpha\beta}$ in the stationary reference frame $\alpha\beta$ by Clarke transformation. Moreover, a linear discrete-time model is used to calculate each future load current which is determined by measured load current and every possible voltage vector. Then the predicted current and reference current are applied to a cost function. The optimal voltage vector is selected which minimizes the cost function. And the switching state associated to the selected voltage vector is set to the gating signals.

SIMULATION RESULTS

Simulations of a three-phase voltage source inverter with RL load were carried out using MATLAB/Simulink. And the model is shown in Fig. 6. System parameters are shown in Table 1.

Figure 7 shows the load current and reference current of the three-phase voltage inverter, where the amplitude of 8A is used.

Figure 8 shows the current spectrum of one phase of the VSI with a Total Harmonic Distortion (THD) of 1.81%. It means the MPC controller provide an accurate current tracking ability with a low THD distortion and low current ripple.

The current step response of the MPC controlled VSI is shown in Fig. 9. The amplitude of the reference

Table 1: Simulation parameters

Parameter	Value
DC link voltage U_{dc}/V	35
Inductance L / mH	5.0
Sampling frequency f_s/kHz	8
Resistance Z/Ω	1
Carrier frequency f/Hz	50

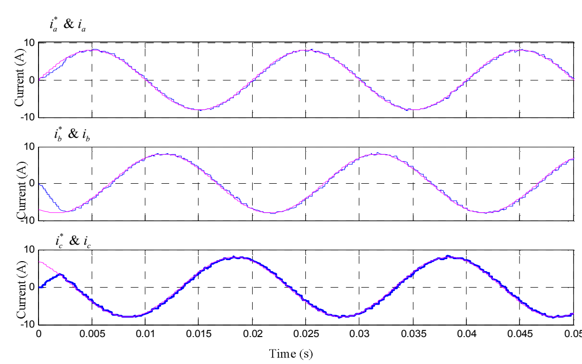

Fig. 6: Three-phase load in the steady state

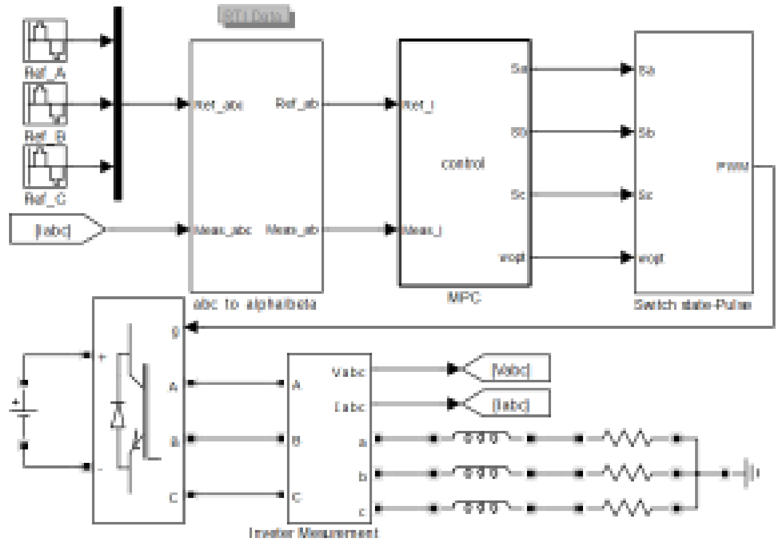

Fig. 7: Simulink model of the VSI

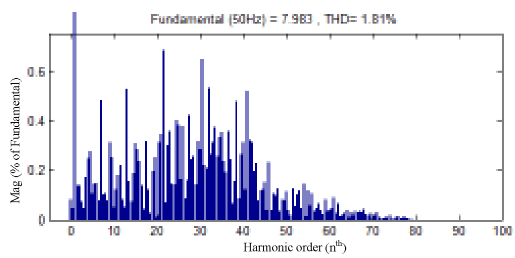

Fig. 8: Current spectrum of a phase

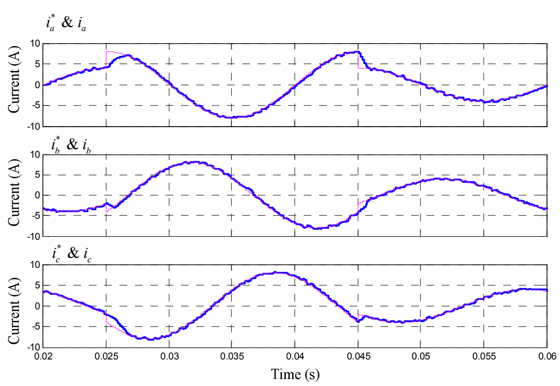

Fig. 9: Three-phase load current transient response for a reference step of 8A-4A at t = 0.025s and 4A-8A at t = 0.045s

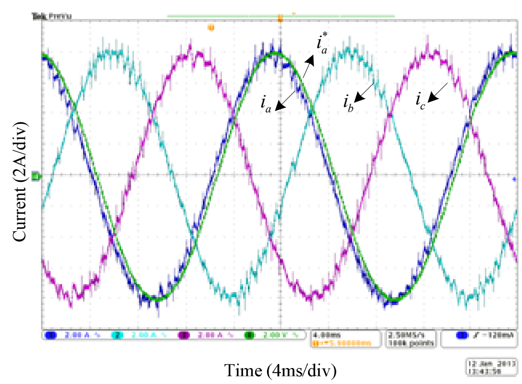

Fig. 10: Experimental load current in the steady state

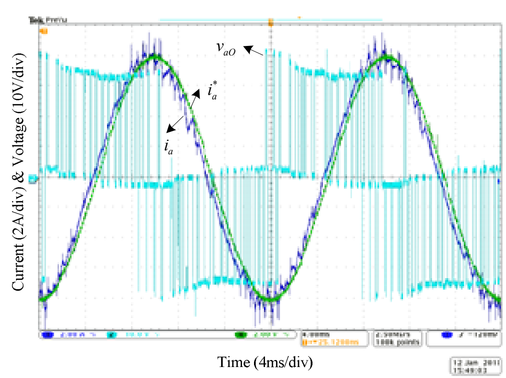

Fig. 11: Experimental load current and phase voltage

current steps from 4A to 8A, then steps from 8A to 4A, which shows the good dynamics ability for tracking reference current.

EXPERIMENTAL RESULTS

The designed control strategy is developed and tested experimentally on a three-phase voltage source inverter with the same parameters shown in Table 1. The model of the control method is developed on MATLAB/simulink. Then the control algorithms are implemented on dSPACE real-time system of ds1104.

Figure 10 shows the load current and reference current with the amplitude of 8A for the three-phase

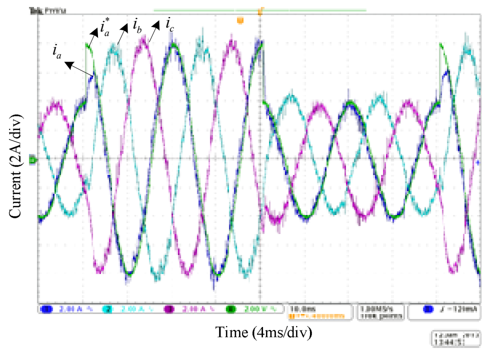

Fig. 12: Three-phase load current transient response for a reference step of 8A-4A and 4A-8A

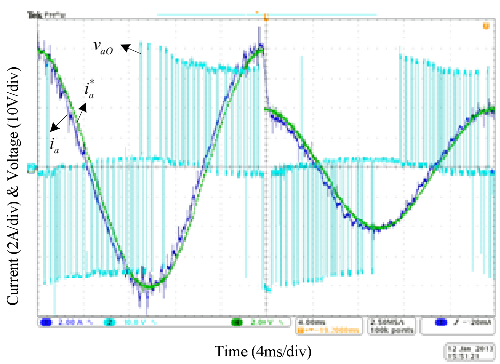

Fig. 13: Experimental load current and phase voltage for step response

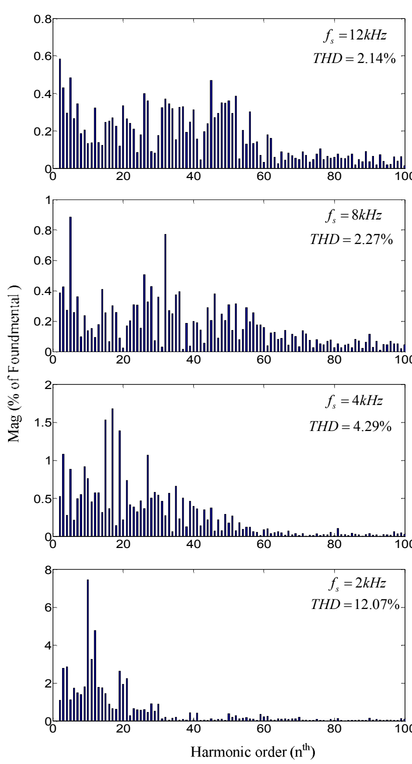

Fig.14: Load current spectrum for different sampling time

voltage inverter. And the phase voltage, load current and reference current are shown in Fig. 11. It is clear that the switching frequency of power devices is much lower than the sampling frequency, although the later is 8 kHz.

Figure 12 shows current step response for experimental results with a current step of 8A-4A and 4A-8A. It is clear that the reference current is followed with fast dynamic behavior, which is similar to the simulation results shown in Fig. 9.

Figure 13 shows the step response of phase voltage, current and reference current of the VSI for a step of 8A-4A.

The effect of changing the sampling frequency is tested and the experimental results are shown in Fig. 14. The load current THD varies with the sampling frequency. The THD is 2.14% with sampling frequency of 12 kHz, 2.27% with 8 kHz, 4.29% with 4 kHz and 12.07% with 2 kHz. It is observed that the performance of the control is improved as the decrease of the sampling time. It also shows the current spectrum spread over a wider frequency range, which is normal lower than half of the sampling frequency. It will bring great challenge for the design of the filter.

CONCLUSION

In this study, a simplified predictive current control technique is applied to a voltage source inverter with MPC controller considering the optimal method of selecting the voltage vector. It will reduce the enormous calculations in the online implementation of MPC. The simulation and experimental results show the g good performances of the current tracking ability in both steady and transient state.

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