A Low-Complexity Optimal Switching Time Modulated Model Predictive Control for PMSM with Three-Level NPC Converter

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Abstract—Conventional finite control set model predictive control (FCS-MPC) presents high computational burden especially in three-level neutral point clamped (NPC) converters. This paper proposes a low-complexity optimal switching time modulated model predictive control (OST-M2PC) method for three-level NPC converter. In the proposed OST-M2PC method, the optimal switching time is calculated using a cost function. Compared to conventional FCS-MPC, the proposed OST-M2PC method has a fixed switching frequency as well as better power quality. The proposed OST-M2PC can operate at a 20kHz sampling frequency, reducing the computational burden of the processor. Simulation and experimental results validate the operation of the proposed method.

Index Terms—Finite control set model predictive control (FCS-MPC), modulated model predictive control (M2PC), permanent magnet synchronous motor (PMSM), optimal switching time modulated model predictive control (OST-M2PC).

I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have been widely used in fields of high-performance servo systems and other industrial applications, due to high efficiency, high power density and other advantages [1]. Generally, a fast current response is required to guarantee high dynamic performance of PMSM drive system. The PI control method is often adopted as the current control method for PMSMs [2]. However, a PI controller is a linear controller with a confliction between system stability and dynamic performance. Some nonlinear methods such as fuzzy control [3], neural network control, sliding mode control [4] and predictive control [5] are gradually being introduced as processor performance improves. Finite control set model predictive control (FCS-MPC) for a three-level neutral point clamped (NPC) converter is firstly introduced by Jose Rodriguez et al. [6]. A discrete time model is used to predict controller current in next sampling period, and all switching actions are evaluated with a cost function. The switching action which minimizes the cost function is selected to be applied to the control system. FCS-MPC generates a switching signal directly, without modulation. FCS-MPC has been widely implemented by the academic and industrial community [7]–[10]. However, FCS-MPC needs high sampling frequency to ensure good control performance, because of variable switching frequency, requiring an often excessive computational time [11].

Several solutions have been proposed to overcome these drawbacks. For example, in [8], Reza Nasiri et al improved the traditional FCS-MPC for a multilevel converter by solving the diophantine equations so that proposed method can run on single core processor. Although this proposed method save most computational time of processor, it still has variable switching frequency. In [12], the duty cycle model predictive control method with a PWM rectifier is proposed. In this method, one nonzero vector is selected and the duty cycle of zero vector is analytically derived. These two vectors are implemented during each sampling period, achieving better steady-state performance. However, only the length of the resultant vector is variable and direction is still fixed. Therefore, it also has an adjustable switching frequency as well as a high current total harmonic distortion (THD). Xiong et al proposed a constant switching frequency MPC method for a five-phase PMSM, which can acquire virtual voltage vectors and their duty ratios by a dead-beat based method directly [1]. However, optimal virtual voltage vectors are selected in two orthogonal subspaces and voltage sequences need to be rearranged by carrier-based pulsewidth modulation (CBPWM), therefore, this proposed algorithm is still complicated. It can be seen from the experiment results that this method can only operate at 10kHz sampling switching using TMS320F28335. To suppress the current ripples of FCS-MPC, a fixed switching method called modulated model predictive control (M2PC) was first proposed by Tarisciotti et al. [13]. This method was applied to a seven-level cascaded H-bridge converter [14] and an indirect matrix converter [15]. In [16], an M2PC is studied for two-level...
voltage source inverter and compared with the traditional FCS-MPC. M2PC has a higher average switching frequency than conventional FCS-MPC at the same sampling frequency as well as better power quality and lower THD. However, this algorithm needs to calculate the two adjacent vectors of all sectors in each sampling period. For a two-level voltage source inverter, the number of calculations is 12, which causes a large computational burden. Meanwhile, duty ratios for the synthesized vectors are evaluated by a cost function, which undermines the accuracy of synthesized vector. M2PC for a three-level NPC converter was first proposed by Rivera et al. [17]. The experimental results of two types of the M2PC methods for a three-level NPC converter were presented by Donoso et al. using a DSPACE-FPGA control platform [18]. More computation time is required for a three-level NPC converter, because for M2PC, it needs to calculate a total of 27 vectors in each sampling period.

In [11], a FCS-MPC method based on predictive voltage control for a three-level NPC converter was proposed to reduce the computational time of the processor. This proposed method has two steps: firstly, the predictive voltage calculation instead of current prediction; Secondly, a reduced number of cost function calculations. In this way, the computation burden of processor is reduced while maintaining the same control performance as conventional FCS-MPC. However, this method is essentially the same as conventional FCS-MPC, which has a variable switching frequency as well as a larger current ripple than M2PC [17]. In [19], an optimal switching sequence model predictive control for a Vienna converter was proposed. The optimal duty ratios can be required by minimizing errors of current. However, the cost function is still a function of actual current and the reference current, the cost function and optimal duty ratios need to be calculated six times in each sampling period, still causing a heavy computation burden.

In order to reduce computation burden of the processor and have a fixed switching frequency to improve harmonic spectrum, a low-complexity optimal switching time modulated model predictive control (OST-M2PC) method for a three-level NPC converter is proposed in this paper. First, a hexagon sector division method is used instead of the triangle sector division method in the three-level phase plane. Small sectors can be quickly selected using the predicted voltage. Then, the dwell times of adjacent vectors in each small sector can be calculated using the cost function, which are the length of the predicted voltage vector and adjacent voltage vectors. Finally, the voltage vector of the next period is synthesized by the dwell times of adjacent vectors. The main research contents of this paper are as follows:

1) The execution time of conventional FCS-MPC is analyzed; a simplified FCS-MPC for three-level NPC converter is introduced.
2) A low-complexity OST-M2PC method is proposed and implementation of this proposed method is described in detail.
3) The execution time for different MPC methods, such as FCS-MPC, M2PC, simplified FCS-MPC and OST-M2PC are compared.

4) The harmonic spectrum of a phase current for simplified FCS-MPC, M2PC and OST-M2PC are analyzed in detail.

The remainder of this paper is organized as follows: Section II introduces the conventional FCS-MPC for PMSM using three-level NPC converter, then introduces a simplified FCS-MPC method. A low-complexity OST-M2PC is given in Section III. Comparative simulation and experimental studies of proposed OST-M2PC and simplified FCS-MPC are presented in Section IV. Finally, the conclusions are drawn in Section V.

II. CONVENTIONAL FINITE CONTROL SET MODEL PREDICTIVE CONTROL METHOD

A. FCS-MPC for PMSM with Three-level NPC Converter

The switching states (P, O, and N) for a typical three-level NPC converter can be seen in Fig. 1.

![Fig. 1. The structure and vector diagram of three-level neutral-point-clamped (NPC) converter.](image)

Assuming that magnetic circuit is not saturated and ignoring hysteresis eddy current [20], [21], the d-q axis voltage model of PMSM is shown in equation (1).

\[
\begin{align*}
\dot{u}_d &= R_i_d + L_d \frac{di_d}{dt} - L_q \omega_i q_d \\
\dot{u}_q &= R_i_q + L_q \frac{di_q}{dt} + L_d \omega_i q_q + \varphi \omega_e 
\end{align*}
\]

$L_q$, $L_d$, and $R_i$ are the $q$-axis inductance, the $d$-axis inductance, and the stator resistance, respectively; $\omega_i$ and $\varphi$ are the electrical speed of PMSM and the flux linkage, respectively. $u_q$, $u_d$ are the $q$-axis voltage, $d$-axis voltage, respectively. Then, a discrete time predictive $d$-$q$ axis currents
can be obtained, as shown in equation (2). \( T_s \) is sampling time, \( k \) is sampling interval.

\[
\begin{align*}
\dot{i}_d^v(k+1) &= \left(1 - \frac{R_T}{L_q}ight) i_d^v(k) + \frac{T_L}{L_q} \omega_d i_q^v(k) + \frac{T_s}{L_q} u_d(k) \\
\dot{i}_q^v(k+1) &= \left(1 - \frac{R_T}{L_q}ight) i_q^v(k) - \frac{T_L}{L_q} \omega_d i_d^v(k) + \frac{\nu \omega T_s}{L_q} + \frac{T_s}{L_q} u_q(k)
\end{align*}
\]

(2)

The conventional FCS-MPC takes all 27 vectors into equation (2) to calculate predictive \( d-q \) axis currents at the next sampling time, then uses the predictive \( d-q \) axis currents to calculate cost function as follows [22].

\[
g = \left(\dot{i}_d^v - \dot{i}_d^v(k+1)\right)^2 + \left(\dot{i}_q^v - \dot{i}_q^v(k+1)\right)^2
\]

(3)

The vector which can minimize the cost function is selected and used in next sampling time. Control diagram of conventional FCS-MPC control method with three-level NPC inverter is shown in Fig. 2. Only one basic vector is selected in each sample period which causes a high current total harmonic distortion (THD) as well as the torque ripple of PMSM [23], see references[17], [24] for details. Meanwhile, a total of 27 basic voltage vectors (including eight redundant voltage vectors) are available in a three-level NPC converter. All vectors need to be predicted by equation (2) and calculated by equation (3), the total calculation time of equation (2) and (3) is 54 in each sampling period, causing a heavy computational burden of processor and hard to run in a high switching frequency.

Substituting the reference \( d-q \) axis currents into equation (4), \( d-q \) axis predictive voltages can be shown as:

\[
\begin{align*}
u_d^v(k) &= R_s i_d + L_q \frac{\dot{i}_d(k+1) - \dot{i}_d(k)}{T_s} - L_q \omega_d i_q^v(k) \\
u_q^v(k) &= R_s i_q + L_q \frac{\dot{i}_q(k+1) - \dot{i}_q(k)}{T_s} + L_q \omega_d i_d^v(k) + \nu \omega
\end{align*}
\]

(4)

Therefore, the \( \alpha-\beta \) axis voltages of predictive vector can be obtained using the inverse Park transformation [25]:

\[
\begin{align*}
u_{d}^* &= u_d^v(k) \cos \theta - u_q^v(k) \sin \theta \\
u_{q}^* &= u_d^v(k) \sin \theta + u_q^v(k) \cos \theta
\end{align*}
\]

(6)

From equation (6), the origin point of selected hexagon can be obtained. \( \theta \) is electrical angle of PMSM. As shown in Fig. 3, the solution of the proposed SFCS-MPC is the same as the conventional two-level FCS-MPC in each hexagon. \( V_t \) and \( u_t^v \) are original voltage vector, new mapping voltage vector, respectively. The new mapping voltage vector in stationary axis can be calculated from Table I.

![Fig. 3 The sector division method of SFCS-MPC for three-level NPC converter.](image)

Then, the cost function can be calculated using the next equation.

\[
g = \left(\nu_{d}^*(k) - \nu_d^v(k)\right)^2 + \left(\nu_{q}^*(k) - \nu_q^v(k)\right)^2
\]

(7)

Where, \( i = 0, \ldots, 6 \). From equation (7), it can be seen that the cost function is the distance of predictive vector and basic vector. This definition of cost function is first proposed by Xia [11]. This proposed FSC-MPC only needs one-time prediction, significantly reduces computational burden of processor.

| TABLE I  | STATIONARY AXIS VOLTAGES IN EACH HEXAGON |
|----------|----------------------------------------|
| Hexagon Sector | \( \alpha \)-axis voltage \( u_{\alpha}^v \) | \( \beta \)-axis voltage \( u_{\beta}^v \) |
| 1        | \( u_{\alpha}^v -V_a/3 \) | \( u_{\beta}^v +V_a/6 \) |
| 2        | \( u_{\alpha}^v +V_a/6 \) | \( u_{\beta}^v -V_a/6 \) |
| 3        | \( u_{\alpha}^v +V_a/3 \) | \( u_{\beta}^v -V_a/3 \) |
| 4        | \( u_{\alpha}^v -V_a/3 \) | \( u_{\beta}^v +V_a/6 \) |
| 5        | \( u_{\alpha}^v +V_a/6 \) | \( u_{\beta}^v +V_a/6 \) |
| 6        | \( u_{\alpha}^v -V_a/6 \) | \( u_{\beta}^v +V_a/3 \) |
III. PROPOSED OST-M2PC METHOD

To reduce the THD of a-phase current using conventional FCS-MPC, a new solution named M2PC which has a fixed switching frequency is developed [26]. In the conventional two-level M2PC method, both predictions and cost functions \(g_1\), \(g_2\) are evaluated by two adjacent vectors in each sector [16]. The total number of calculations is 12. In three-level M2PC method, the total number of calculations is 72, because there are 24 small sectors, each of which has three large voltage vectors. Details of M2PC method for three-level NPC converter can be found in [17], [18]. The conventional M2PC has a fixed switching frequency as well as better power quality than FCS-MPC. However, the number of executions of (2) and (3) in the conventional M2PC is 144 [17], which increases the computation burden of the processor. Due to limited space of this paper, please refer to references [17], [23] for details of M2PC. This paper introduces a low-complexity OST-M2PC to reduce the calculation burden. Different from the conventional M2PC, the proposed OST-M2PC adopts predictive voltages in next sampling time, as shown in equation (5). Only one-time prediction is needed (the number of executions of (5) is 1) in each sampling period and one sector is selected by predictive voltage quickly, reducing the computation time. The sector division method of this proposed technique still adopts six hexagon division, as shown in Fig. 3.

A. Sector Selection of Proposed OST-M2PC

The large hexagon sector can be selected by static coordinate predictive voltage vector. Each large hexagon sector is located in the fixed angle range by equation (8) and Table II.

\[
\begin{align*}
    u^p_\alpha > 0 & \quad A = 1, \text{otherwise}, A = 0 \\
    \sqrt{3}u^p_\alpha + 3u^p_\beta > 0 & \quad B = 1, \text{otherwise}, B = 0 \\
    3u^p_\beta - \sqrt{3}u^p_\alpha > 0 & \quad C = 1, \text{otherwise}, C = 0 \\
    N = 4A + 2B + C
\end{align*}
\]  

(8)

Each large sector has its own six small sectors. The new mapping voltage vector in static coordinate can be determined from Table II. The space vector diagram of three-level is converted to that of two-level by shifting origin point of each large sector, as shown in Fig. 3.

A total of six small sectors in each large sector, the selection of each small sector is same as conventional two-level space vector pulse width modulation (SVPWM) method. Taking the first large sector as an example, the predictive voltage vector in the stationary axis are \(u^p_{\alpha_2}(k)\), \(u^p_{\beta_2}(k)\), respectively. The small sector can be selected using equation (9) and Table III.

\[
\begin{align*}
    u^p_{\alpha_2} > 0 & \quad X = 1, \text{otherwise}, X = 0 \\
    \sqrt{3}u^p_{\alpha_2} - u^p_{\beta_2} > 0 & \quad Y = 1, \text{otherwise}, Y = 0 \\
    -\sqrt{3}u^p_{\alpha_2} - 3u^p_{\beta_2} > 0 & \quad Z = 1, \text{otherwise}, Z = 0 \\
    M = X + 2Y + 4Z
\end{align*}
\]  

(9)

B. Optimal Switching Time Calculation of Proposed Method for Three-level NPC Converter

In the conventional M2PC method, dwell times for two adjacent voltage vectors and the zero voltage vector are calculated from a proportional relationship. The switching frequency can be fixed by modulation, but the dwell times of the adjacent voltage vectors are not optimal. To overcome this problem, this paper presents an optimal switching time calculation method which is similar to the one proposed by Shin-Won et al. [27]. Reference [27] uses the cost function to calculate the optimal duration ratio of the symmetrical three vector for two-level voltage source inverter. Here, through expanding this method to a three-level NPC converter, calculating the optimal switching time in the selected mapping small sector is proposed. Take first small sector of large sector for example, as shown in Fig. 4, the dwell times of two adjacent vectors and zero vector are \(T_a\), \(T_c\), \(T_d\), respectively. Therefore, the resultant vector in stationary coordinate can be defined as follows:

\[
\begin{align*}
    T_aV_a &= V_{a1}T_a + V_{a2}T_c + V_{a0}T_d \\
    T_cV_c &= V_{c1}T_a + V_{c2}T_c + V_{c0}T_d \\
    T_dV_d &= V_{d1}T_a + V_{d2}T_c + V_{d0}T_d
\end{align*}
\]  

(10)

Where, \(V_{a1}\), \(V_{a2}\), \(V_{a0}\) are the \(\alpha\)-axis component of voltage vector \(V_a\), \(V_c\) and \(V_d\), \(V_{c1}\), \(V_{c2}\), \(V_{c0}\) are the \(\beta\)-axis component of voltage vector \(V_c\) and \(V_d\). As shown in equation (11), the new dwell times \(d_1\), \(d_2\), \(d_0\) can be obtained by normalizing dwell times \(T_1\), \(T_2\), \(T_0\), respectively.

\[
\begin{align*}
    V_a &= V_{a1}d_1 + V_{a2}d_2 + V_{a0}d_0 \\
    V_c &= V_{c1}d_1 + V_{c2}d_2 + V_{c0}d_0 \\
    V_d &= V_{d1}d_1 + V_{d2}d_2 + V_{d0}d_0 \\
    d_0 &= T_0/T_a \\
    d_1 &= T_1/T_a \\
    d_2 &= T_2/T_a
\end{align*}
\]  

(11)

The proposed OST-M2PC can find out the optimal dwell times of resultant voltage vectors as well as solving optimal \(d_1\), \(d_2\), \(d_0\). Therefore, the cost function can be defined as follows:

\[
g = (u^p_{\alpha_2} - V_a)^2 + (u^p_{\beta_2} - V_c)^2
\]  

(12)

\(u^p_{\alpha_2}\) and \(u^p_{\beta_2}\) are the predictive voltages in mapping small sector. Optimal dwell times of resultant voltage vectors can be solved using equation (13).
The target speed is 1000 rpm. The waveform spectrum for these three phase current operating with M2PC. shows three phase current and d-q axis currents of SFCS-MPC, respectively. Fig. 7 shows responses of d-q axis currents and three phase current operating with M2PC. The d-q axis currents and a phase current of proposed OST-M2PC are shown in Fig. 8. From Figs. 6-8, the dynamic responses of these three approaches can be seen to be exactly the same. However, the M2PC has a lower current ripple than the SFCS-MPC. The proposed OST-M2PC has a lowest current ripple by calculating optimal dwell times. The waveform spectrum for these three methods at steady 1500rpm are shown in Figs. 9, 10 and 11, respectively.

Fig. 5 shows the flow chart for the proposed OST-M2PC, this flow chart begins with the calculation of d-q axis predictive voltages of PMSM. Then, the α-β axis predictive voltages in selected large sector can be obtained in Table I. Two adjacent voltage vectors and small sector can be selected by mapping α-β axis predictive voltages. Finally, the cost function can be calculated with the resultant voltage vectors and predictive voltage vectors for comparison of minimal. The dwell times of the two adjacent voltage vectors can be obtained and applied.

IV. SIMULATION AND EXPERIMENTAL RESULTS

Simulation and experimental results have been used to validate the proposed OST-M2PC and SFCS-MPC in a PMSM system with a three-level NPC converter. The parameters of the PMSM are shown in Table IV. The sampling frequency of the three-level NPC converter is 20kHz.

| Parameter                  | Symbol | Value      |
|----------------------------|--------|------------|
| Rated Voltage              | V      | 230 V      |
| Stator Phase Resistance    | R      | 1.2 Ω      |
| Motor Inertia              | J      | 0.0116 kg.m² |
| Pole Pairs                 | p      | 3 Pair     |
| Rated Torque               | T_r    | 8.1 N.m    |
| q-axis Inductance          | L_q    | 8.379 mH   |
| d-axis Inductance          | L_d    | 6.17 mH    |
| Machine mutual flux        | ψ_n   | 0.23 Vs    |
| Viscous damping            | B      | 0.0015 Nms |

A. Simulation Results

Figs. 6, 7 and 8 show dynamic load disturbance simulation results of the SFCS-MPC, M2PC [17] and the proposed OST-M2PC, respectively. The target speed is 1000rpm. An external torque load is applied to test system at t = 0.3s. The q-axis current increases quickly, showing the robustness of the control system to a load disturbance. From Fig. 6 (a)-(c), shows three phase current and d-q axis currents of SFCS-MPC, respectively. Fig. 7 shows responses of d-q axis currents and three phase current operating with M2PC. The d-q axis currents and a phase current of proposed OST-M2PC are shown in Fig. 8. From Figs. 6-8, the dynamic responses of these three approaches can be seen to be exactly the same. However, the M2PC has a lower current ripple than the SFCS-MPC. The proposed OST-M2PC has a lowest current ripple by calculating optimal dwell times. The waveform spectrum for these three methods at steady 1500rpm are shown in Figs. 9, 10 and 11, respectively.
Fig. 6. Simulation results of SFCS-MPC. (a) A-phase current. (b) A-phase current (0.35s-0.4s). (c) d-q axis currents.

Fig. 7. Simulation results of M2PC. (a) A-phase current. (b) A-phase current (0.35s-0.4s). (c) d-q axis currents.

Fig. 8. Simulation results of proposed OST-M2PC. (a) A-phase current. (b) A-phase current (0.35s-0.4s). (c) d-q axis currents.

Fig. 9. The output waveform spectrum for SFCS-MPC (simulation). (a) A-phase current. (b) Harmonic spectrum of A-phase current.
Fig. 10. The output waveform spectrum for M2PC (simulation). (a) A-phase current. (b) Harmonic spectrum of A-phase current.

Fig. 11. The output waveform spectrum for OST-M2PC (simulation). (a) A-phase current. (b) Harmonic spectrum of A-phase current.

TABLE V
THD OF A-PHASE CURRENT UNDER VARIOUS SPEED

| Speed   | Methods   | THD   |
|---------|-----------|-------|
| 600rpm  | SFCS-MPC  | 3.76% |
|         | M2PC      | 3.16% |
|         | OST-M2PC  | 2.45% |
| 1000rpm | SFCS-MPC  | 4.07% |
|         | M2PC      | 1.99% |
|         | OST-M2PC  | 0.41% |
| 1500rpm | SFCS-MPC  | 4.55% |
|         | M2PC      | 1.94% |
|         | OST-M2PC  | 1.70% |

The THD of the SFCS-MPC method, M2PC method and proposed OST-M2PC method are 4.55%, 1.94% and 1.7%, respectively. The THD of a-phase current at different speeds is summarized in Table V. It can be seen that the proposed OST-M2PC has the lowest THD as well as better power quality than the other two methods.

B. Experimental Results

A prototype PMSM control system with a three-level NPC converter was built to test the proposed method. Fig. 12 shows the photograph of the experimental test rig. The PMSM (Emerson, 115UMC Series) is powered by a three-level NPC converter. A DC motor (TT Electric, LAK 2100-A) is used as a load. The main controller is a floating digital signal processor (Texas Instrument, TMS320F28335) running with a 150MHz clock frequency. All experimental results are from an oscilloscope with a 12-bit high-speed digital analog (DA) converter. The sampling time is 50 $\mu$s.

Fig. 12. Photograph of experimental test rig with three-level NPC converter.

The running time in each sample period can be seen from Fig. 13. For different MPC algorithms, only the running time of step 4 is different. The running time required in TMS320F28335 by different methods in step 4 are shown in Table IV. As seen in this table, the running time of conventional FCS-MPC, MP2C [17], SFC-M2PC and OST-M2PC are obtained using CCS 6.2 (Texas Instrument Company, Code Composer Studio Integrated Development Environment) are 218 $\mu$s, 384 $\mu$s, 17.6 $\mu$s and 26.7 $\mu$s, respectively. FCS-MPC and MP2C cannot run in one sampling period (50 $\mu$s in one sampling period). Therefore, only comparison experiments for SFCS-MPC and OST-M2PC methods are implemented at 20kHz sampling frequency. The proposed SFCS-MPC and OST-M2PC reduce the computational burden of processor, but the OST-M2PC needs more running time than SFCS-MPC.

![Fig. 13. Running time required in each sample period.](image)

1: AD sample and angle measure
2: Coordinate transformation
3: Speed PI calculate
4: Predictive control algorithm
5: Free time
Figs. 14-16 show dynamic response abilities of the OST-M2PC and SFCS-MPC methods. Fig. 14 shows experimental results under speed changing from 200rpm to 1000rpm. SFCS-MPC and proposed OST-M2PC have the same dynamic performance. The PMSM can achieve target speed 1000rpm within 200ms. Fig. 15 shows experimental results under speed changing from 1000rpm to 200rpm. It is clearly seen that the speed of PMSM tracks the target speed quickly and accurately. The current ripples of SFCS-MPC are much higher than proposed OST-M2PC. Fig. 16 shows experimental results under sudden load disturbance at 1000rpm. The proposed OST-M2PC and SFCS-MPC have same disturbance rejection potential as well as fast response ability of current loop, the speed of PMSM can recovery within 100ms.

Figs. 17-18 show the steady responses for the OST-M2PC and SFCS-MPC methods. The harmonic analysis of SFCS-MPC and OST-M2PC are shown in Figs. 17 and 18, respectively. It can be seen that the THD for the SFCS-MPC and OST-M2PC are 5.66% and 3.01%, respectively. The proposed OST-M2PC has lower current ripple than SFCS-MPC.

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### Table IV

| Method          | FCS-MPC | M2PC | SFCS-MPC | OST-M2PC |
|-----------------|---------|------|----------|----------|
| Running time required in TMS320F28335 | 218 µs  | 384 µs | 17.6 µs  | 26.7 µs  |

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### Fig. 14

Experimental results under target speed changing from 200rpm to 1000rpm. (a) SFCS-MPC. (b) OST-M2PC.

### Fig. 15

Experimental results under speed changing from 1000rpm to 200rpm. (a) SFCS-MPC. (b) OST-M2PC.

### Fig. 16

Experimental results under sudden load disturbance at 1000rpm. (a) SFCS-MPC. (b) OST-M2PC.

### Fig. 17

The wave spectrum for SFCS-MPC (Experimental results). (a) A-phase current. (b) Harmonic spectrum of a-phase current.
This paper presents a low-complexity optimal switching time modulated model predictive control (OST-M2PC) method for PMSM with three-level NPC converter. Different from the conventional FCS-MPC, the optimal switching time of OST-M2PC can be calculated by a cost function, which has a fixed switching frequency as well as better power quality. The proposed OST-M2PC method is easy to be implemented in a three-level NPC converter. The conventional FCS-MPC cannot run with a high sampling frequency because of computing limitation of the processor. To confirm the effects of OST-M2PC method and compare with the traditional FCS-MPC method at a high sampling frequency, a simplified finite control set model predictive control (SFCS-MPC) for a three-level NPC converter is proposed. The use of OST-M2PC shows reduced current ripple from simulation and experimental results. However, similar with other MPC methods, OST-M2PC is still a model-based approach. When the motor parameters are not accurate, the control performance will be affected. As for future works, the proposed OST-M2PC with an actual parameter disturbance observer such as luenberger [28], ESO [29], [30] or SMO [31] based approach will be used to improve robust ability of OST-M2PC.

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