Improved Deadbeat-Predictive Torque Control Space Vector Modulation method with Open-End Winding Interior Permanent Magnet Synchronous Motor

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***Abstract*—This paper proposes an improved deadbeat-predictive torque control (DB-PTC) using space vector modulation (SVM) to drive open-end winding interior permanent magnet synchronous motor (OEW-IPMSM). Conventional predictive torque control (C-PTC) directly applies the voltage vector which closely follows the reference. Therefore, it has good transient response characteristics and simple algorithms. However, C-PTC applies the voltage vectors that have fixed magnitude in a single sampling period, which makes inconsistent switching frequency and high torque ripples. The proposed DB-PTC method selects the specific region where the virtual voltage vectors generated by the estimated reference voltage angle and cost function. Virtual voltage vectors offer to apply an optimal voltage vector, and the SVM method makes having consistent switching frequency. In result, steady state error can be decreased, the proposed method has a great advantage in terms of torque ripple reduction. The validity of proposed DB-PTC method is demonstrated through the simulation results.**

Index Terms-deadbeat, predictive torque control, space vector modulation, open-end winding, IPMSM, torque ripple reduction

I. Introduction

Predictive torque control (PTC) in voltage source inverter (VSI) aims to predict output in the next control period through the value of current according to the motor modeling equation, and to apply the reference voltage vector that has the smallest error from the reference value. In general, PTC directly applies the voltage vector with the least error with the reference without controllers compared to the existing control methods such as PI control. Therefore, it has fast dynamic response with a simple structure of control algorithms, consequently PTC is widely used in various industries and actively studied. However, conventional predictive torque control (C-PTC) has inconsistent switching frequency and high torque ripple caused by directly applied only one voltage vector per a control period. Corresponding disadvantages make worse at the steady state character of PTC [1]-[2].

In order to drive the interior permanent magnet synchronous motor (IPMSM) using PTC, the stator magnet flux and torque of the next control period are predicted through each stator winding current and existing voltage vectors, and the reference voltage vector is selected by the cost function and applied to VSI [3]. The cost function stores the voltage vector that generates the minimum error between the stator magnet flux or torque reference and predict value until the all of the errors calculated. A large steady state error in the PTC causes large torque ripples and decreasing in stator currents quality of IPMSM.

Deadbeat predictive torque control (DB-PTC) with space vector modulation (SVM) method applies voltage vectors including the virtual voltage vectors that other than in the actual switching states. Virtual voltage vectors are generated temporarily in the specific region of the voltage vector diagram of stationary reference frame [4]. As the number of virtual voltage vectors increases, more optimal voltage vector could be selected, but this causes a calculation burden on the microprocessor [5]-[6]. In order to reduce calculation burden, deadbeat method needs to be applied to limit generation of unsuitable virtual voltage vectors. By applying the deadbeat method, only certain virtual voltage vectors are used to predict the values of the next control period. Like C-PTC, generated virtual voltage vectors are used to predict stator flux and torque in the next control period, and selects the optimal voltage vector that is the closest to reference by the cost function. Selected voltage vector applies to SVM method which decides the switching states with consistent switching frequency. Generated voltage vectors and consistent switching frequency make effects to improve in steady state characteristics, ultimately to decrease the torque ripple and improve the stator currents quality [7].

This paper proposes improved DB-PTC with SVM method for decreasing torque ripple when driving open-end winding interior permanent magnet synchronous motor (OEW-IPMSM) fed by the dual inverter. In the proposed method, virtual voltage vectors are generated in a specific segmented region based on the estimated reference voltage angle and the cost function. The selected specific region reduces calculation burden on the microprocessor and enables the selection of virtual voltage vectors more optimal for following reference torque. As a result, compared to C-PTC method, the proposed method has the effect on reducing torque ripple, thereby improving steady state and current quality. The simulation results are presented to demonstrate the validity of the proposed DB-PTC method in comparison with C-PTC method.

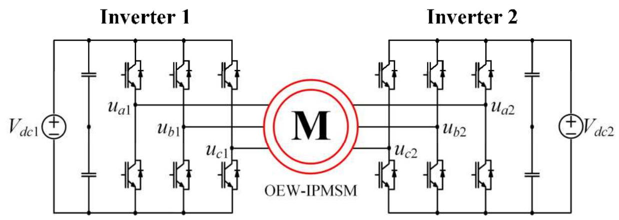

Fig. 1. Circuit diagram for driving OEW-IPMSM.

II. Modelling of OEW-IPMSM fed by Dual Inverter

In order to drive OEW-IPMSM, the dual inverter is used among the various types of VSI for linking two ends of the stator winding. Fig. 1 shows a circuit diagram for driving OEW-IPMSM system fed by the dual inverter that includes isolated DC-link voltage sources. In dual inverter, each a, b, and c phase voltage of inverter 1 and inverter 2 have 180˚ phase difference. Therefore, phase voltages that applied to OEW-IPMSM are generated by difference between phase voltages of inverter 1 and inverter 2, and expressed as

$$
\begin{aligned}
&u_{as} = u_{a1} - u_{a2}\\
&u_{bs} = u_{b1} - u_{b2}\\
&u_{cs} = u_{c1} - u_{c2}\\
&u_{a(n)} = V_{dc(n)} \cdot \left(2S_{a(n)} - S_{b(n)} - S_{c(n)}\right)/3\\
&u_{b(n)} = V_{dc(n)} \cdot \left(2S_{b(n)} - S_{c(n)} - S_{a(n)}\right)/3\\
&u_{c(n)} = V_{dc(n)} \cdot \left(2S_{c(n)} - S_{a(n)} - S_{b(n)}\right)/3
\end{aligned} \tag{1}
$$

where n, u_{abc}, u_{abcs}, V_{dc}, S_{abc} represents inverter 1 or inverter 2, phase voltages of each inverter, phase voltages of dual inverter, DC-link voltage, and switching states for each phase, respectively.

Modelling equation of the OEW-IPMSM are usually used in stationary or rotor reference frame. The d-q axes voltage of OEW-IPMSM in rotor reference frame is expressed as

$$
\begin{aligned}
v_{de} &= R_s \cdot i_{de} + \frac{d\lambda_{de}}{dt} - \omega_r \cdot \lambda_{qe}\\
v_{qe} &= R_s \cdot i_{qe} + \frac{d\lambda_{qe}}{dt} + \omega_r \cdot \lambda_{de}
\end{aligned} \tag{2}
$$

where v_{dqe}, i_{dqe}, λ_{dqe} represent d-q axes stator voltage, stator current, stator linkage flux in rotor reference frame, and ω_r, R_s represent motor speed, stator resistance, respectively. The electromagnetic torque and stator linkage flux equations are also modelled in the rotor reference frame and as follows

$$
\begin{aligned}
&T = \frac{3}{2} \cdot \frac{P}{2} \cdot \left[\lambda_f \cdot i_{qe} + \left(L_d - L_q\right) \cdot i_{de} \cdot i_{qe}\right]\\
&\lambda_{de} = L_d \cdot i_{de} + \lambda_f\\
&\lambda_{qe} = L_q \cdot i_{qe}
\end{aligned} \tag{3}
$$

where λ_f, T, P, L_{dq} represent the permanent magnet linkage flux, electromagnetic torque, the number of poles, and the stator inductance of d-q axes, respectively.

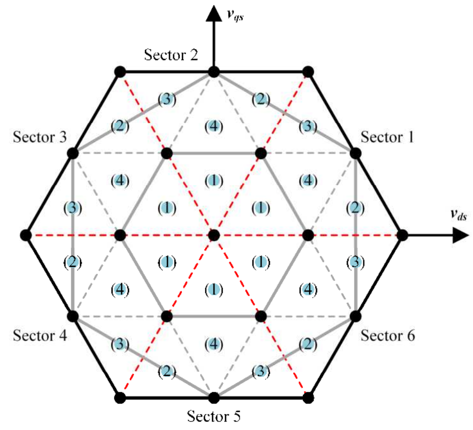

Fig. 2. Voltage vector diagram with divided sectors.

III. Principles of C-PTC Method

The C-PTC method is directly applied the voltage vectors that having real switching states. In OEW-IPMSM driving system fed by the dual inverter which applied identical magnitude of isolated DC-link voltage sources has 19 switching states which shown in Fig.2 as black dots. C-PTC method calculates electromagnetic torque and stator linkage flux by currents of next control period with corresponding voltage vectors.

Using voltage equation in Eq. (2) and stator linkage flux equation in Eq. (3), continuous currents model of OEW-IPMSM is derived and expressed as

$$
\begin{aligned}
v_{de} &= R_s\, i_{de} + L_d \frac{di_{de}}{dt} - \omega_r L_q i_{qe}\\
v_{qe} &= R_s\, i_{qe} + L_q \frac{di_{qe}}{dt} + \omega_r L_d i_{de} + \omega_r \lambda_f
\end{aligned} \tag{4}
$$

in the rotor reference frame. Continuous currents model needs to transform into discrete currents model to derive currents of next control period. In order to convert t of analog time components contained in the continuous currents model to digital components T_s of a discrete currents model, the differential term is approximated as

$$
\frac{di}{dt} \cong \frac{i(k) - i(k-1)}{T_s} \approx \frac{i(k+1) - i(k)}{T_s} \tag{5}
$$

where i, T_s, represent components of currents, control period, and k−1, k, k+1 means the value of the previous, the current, and the next period, respectively. According to the approximation in Eq. (5), discrete current model is derived as

$$
\begin{aligned}
i_{de}(k+1) =& \left(1 - R_s \cdot T_s / L_d\right) \cdot i_{de}(k)\\
&+ \left(L_q \cdot T_s / L_d\right) \cdot \omega_r \cdot i_{qe}(k)\\
&+ v_{de}(k+1) \cdot T_s / L_d\\
i_{qe}(k+1) =& \left(1 - R_s \cdot T_s / L_q\right) \cdot i_{qe}(k)\\
&+ \left(L_q \cdot T_s / L_d\right) \cdot \omega_r \cdot i_{de}(k)\\
&+ v_{qe}(k+1) \cdot T_s / L_q - \lambda_f \cdot \omega_r \cdot T_s / L_q
\end{aligned} \tag{6}
$$

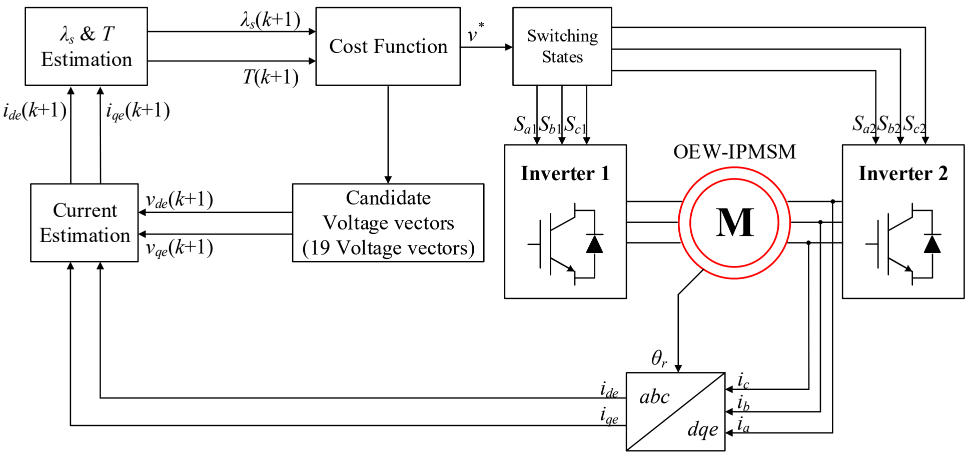

Fig. 3. Block diagram for C-PTC method.

Using discrete currents model, by currents in the next control period is estimated through the sensed currents, which means the current control period values, and the voltage to be used.

From estimated currents, the electromagnetic torque and the stator linkage flux are also estimated and as follows

$$\lambda_s(k+1)=\sqrt{\left(L_d\, i_{de}(k+1)+\lambda_f\right)^2+\left(L_q\, i_{qe}(k+1)\right)^2}$$
$$T\,(k+1)=\frac{3}{2}\cdot\frac{P}{2}\cdot\left[\lambda_s(k+1)i_{qe}(k+1)\right.$$
$$\left.+\left(L_d-L_q\right)i_{de}(k+1)\, i_{qe}(k+1)\right] \tag{7}$$

where λ_s represents the magnitude of stator linkage flux. The estimated stator linkage flux and electromagnetic torque in C-PTC method are controlled to follow reference values. Within 19 voltage vectors in Fig. 2, an optimal voltage vector which makes the stator linkage flux and electromagnetic torque of next control period closet to the reference is applied. In order to select optimal voltage vector, the error between estimated values and reference values are calculated by the cost function. For generation of required stator linkage flux and electromagnetic torque, the cost function considers two corresponding terms simultaneously, and expressed as

$$J=F_\lambda\cdot\left|\lambda_s^*-\lambda_s(k+1)\right|+F_T\cdot\left|T^*-T(k+1)\right| \tag{8}$$

where J, F_λ, F_T represent cost function value, weighting factor for stator linkage flux, and weighting factor for electromagnetic torque. The cost function includes weighting factors to compensate for the difference in error magnitude ratios. Magnitude of weighting factors are determined by empirical values or ratio according to rated value. After calculating all cost function values for the voltage vector candidates, the optimal voltage vector having the minimum cost function value is selected as the reference voltage vector. When the reference voltage vector is determined, the switching state is directly applied to the dual inverter every control period. Fig. 3 shows for block diagram for C-PTC method. Selected reference voltage vector is directly applied as switching states and shown in Table I, where v_{ds}, v_{qs} represent voltage vector value of d-q axes in stationary reference frame.

TABLE I
SWITCHING STATES BY VOLTAGE VECTORS

Voltage vector	v_{ds}	v_{qs}	S_a	S_b	S_c
0, 7	0	0	0 1	0 1	0 1
1	$2V_{dc}/3$	0	1	0	0
2	$V_{dc}/3$	$V_{dc}/\sqrt{3}$	1	1	0
3	$-V_{dc}/3$	$V_{dc}/\sqrt{3}$	0	1	0
4	$-2V_{dc}/3$	0	0	1	1
5	$-V_{dc}/3$	$-V_{dc}/\sqrt{3}$	0	0	1
6	$V_{dc}/3$	$-V_{dc}/\sqrt{3}$	1	0	1

IV. Proposed DB-PTC with SVM Method

Proposed DB-PTC with SVM method includes deadbeat method that designating the specific region where the virtual voltage vectors generated. Specific region needs to be determined for reduction of calculation burden on microprocessors. A number of calculations for the cost function by candidate voltage vectors takes a long computation time. If the computation time is longer than control period, it causes out of control or the cost function calculation for all voltage vector candidates is not be possible. In the selected region, virtual voltage vectors are generated to select the optimal reference voltage vector that having minimum error values of stator linkage flux and electromagnetic torque.

A. Determining virtual voltage vectors generation region

Determining the specific region is consists of two steps. First step is the estimating the reference voltage vector angle of the OEW-IPMSM applying voltage model equation. Estimated voltage from the voltage model equation is expressed as

$$\hat{v}_{de}=\left(R_s+L_d/T_s-L_q/T_s\right)i_{de}-\left(L_d\omega_r\right)i_{qe}$$
$$\hat{v}_{qe}=\left(R_s+L_q/T_s-L_d/T_s\right)i_{qe}+\left(L_q\omega_r\right)i_{de}+\omega_r\,\lambda_f \tag{9}$$

where $\hat{v}_{dqe}$ represents rotor reference frame d-q axes voltage, which is estimated. Eq. (9) is transformed into

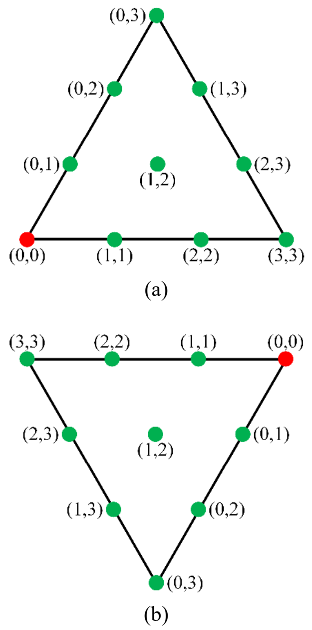

Fig. 4. Example of generating virtual voltage vectors(N=3)
(a) For non-inverted triangle region (b) For inverted triangle region.

stationary reference frame for estimating reference voltage angle and expressed as

$$\theta_v = \tan^{-1}\left(\frac{\hat{v}_{qs}}{\hat{v}_{ds}}\right) \tag{10}$$

where θ_v, $\hat{v}_{dqs}$ represent estimated reference voltage angle and stationary reference frame d-q axes voltage, which is estimated. The specific region is selected as sector through the reference voltage angle. Sectors are shown in Fig. 2 from sector 1 to sector 6 every 60° degrees separated by red dotted line.

Next step is for determination of virtual voltage vectors generation region. After the sector is determined, the cost function is used to select the smaller specific region in the determined sector. The sector that determined from the reference voltage angle is divided into four equilateral triangles, and the temporary virtual voltage vectors are generated at the center of mass of each triangle. The generated temporary virtual voltage vectors in each sector are represented in Fig. 2 as blue dots and used in the next control period's current estimation by Eq. (6). By the estimated currents, the stator linkage flux and electromagnetic torque are estimated by Eq. (7). When the cost function from the Eq. (8) has minimum value, the corresponding temporary virtual voltage vector is selected. The triangle which the selected temporary virtual voltage vector exists is determined as the virtual voltage vectors generation region. In Fig. 2, the virtual voltage vectors generation region is indicated by triangle 1 to triangle 4 on the blue dots for each sector.

B. Generating virtual voltage vectors

After the process of determining virtual voltage vectors generation region of two steps, virtual voltage vectors are generated in the determined triangle. The number of voltage vectors are determined by the subdividing constant (N) and each virtual voltage vector has its own two-dimensional coordinate coefficients shown as

TABLE II
COEFFICIENTS BY SHAPE OF REGION

Coefficients by shape of region	Non-inverted triangle	Inverted triangle
a	0.5	−0.5
b	0.5	−0.5
c	−1	1
d	1	−1

$$\begin{aligned} x &\in \{0,\ 1,\ 2,\ \ldots,\ y\} \\ y &\in \{0,\ 1,\ 2,\ \ldots,\ N\} \end{aligned} \tag{11}$$

where x and y represent the coordinate coefficients of virtual voltage vectors in stationary d-q axes frame. Fig. 4 shows the example of generating of virtual voltage vectors when the subdividing constant is 3. The number on the virtual voltage vectors represent coordinate coefficients, and the red virtual voltage vector is the datum point for the deriving the magnitude of virtual voltage vectors. Datum points are calculated from the selected temporary virtual voltage vectors which represent the center of mass in the selected triangle. The shape of the triangle consists of non-inverted triangle and inverted triangle. Depending on the shape of the triangle, the datum point calculation method is also expressed differently, and in the case of non-inverted triangle, datum point is expressed as

$$\begin{aligned} v_{ds(0)} &= v_{ds(M)} - (V_{dc1} + V_{dc2})/6 \\ v_{qs(0)} &= v_{qs(M)} - \sqrt{3}(V_{dc1} + V_{dc2})/18 \end{aligned} \tag{12}$$

where $v_{dqs(M)}$, $v_{dqs(0)}$ represent the value of center of mass, and datum point of the triangle, respectively. In the case of inverted triangle, datum point is expressed as

$$\begin{aligned} v_{ds(0)} &= v_{ds(M)} + (V_{dc1} + V_{dc2})/6 \\ v_{qs(0)} &= v_{qs(M)} + \sqrt{3}(V_{dc1} + V_{dc2})/18 \end{aligned} \tag{13}$$

The calculated datum points are the coordinate of the (0, 0). By the calculated datum point and coordinate coefficients, the magnitude of virtual voltage vectors is derived. In addition, the magnitude of virtual voltage vectors is also calculated according to shape of triangle. Additional coefficients by shape of region are shown in Table II and expressed as a, b, c, and d. Accordingly, the magnitude of virtual voltage vectors is as follows

$$\begin{aligned} v_{ds(vir)} &= v_{ds(0)} + (V_{dc1} + V_{dc2}) \cdot (ax + by)/3N \\ v_{qs(vir)} &= v_{qs(0)} + \sqrt{3} \cdot (V_{dc1} + V_{dc2}) \cdot (cx + dy)/6N \end{aligned} \tag{14}$$

where $v_{dqs(vir)}$ represents the stationary reference frame d-q axes voltage of virtual voltage vectors.

When the proposed deadbeat method is not applied, the number of calculations by subdividing constants is expressed as

$$C(N) = 6 \cdot [(2N)!] \tag{15}$$

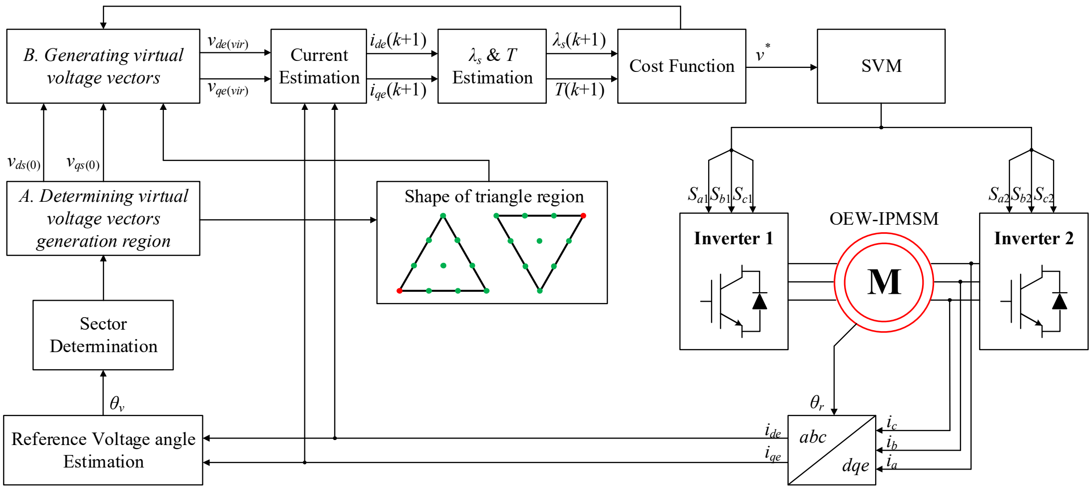

Fig. 5. Block diagram for proposed DB-PTC with SVM method.

where $C(N)$ represents the number of calculations by subdividing constants in non-deadbeat method. However, when the proposed deadbeat method is applied, the number of calculations by subdividing constants is expressed as

$$C_{DB}(N)=(N+1)!+4 \tag{16}$$

where $C_{DB}(N)$ represents the number of calculations by subdividing constants in proposed DB-PTC method. When the proposed DB-PTC method is applied, microprocessors have smaller calculation burden. For instance, if the user applied subdividing constants as 3, the number of calculations reduce 126 to 14.

C. SVM and overall block diagram

After virtual voltage vectors are generated, like in C-PTC method the reference voltage vector is determined by Eq. (6), Eq. (7), and Eq. (8). However, in the proposed DB-PTC method, the selected reference voltage vector applied to SVM method, which is determining switching states compares with triangular waves. In addition, offset voltages are also included for symmetric switching states.

Fig. 5 shows block diagram for proposed DB-PTC with SVM method. Proposed deadbeat method reduces the number of calculations, and generates virtual voltage vectors in smaller voltage vector region. The determined reference voltage vector is modulated to compare with triangular waves. The SVM method makes switching frequency constantly, and the DB-PTC method makes determining more optimal reference voltage vector with smaller error in stator linkage flux or electromagnetic torque.

TABLE III
OEW-IPMSM PARAMETERS

Parameters	Values	Units
Rated power	2.2	kW
Rated speed	1750	rpm
Rated electromagnetic torque	12	Nm
The number of poles	12	-
Stator resistance	0.213	Ω
d-axis inductance	1.6	mH
q-axis inductance	2.18	mH
Permanent magnet flux	0.1133	Wb

V. SIMULATION RESULTS

The proposed DB-PTC with SVM method was verified by PSIM simulation results. Table III shows the OEW-IPMSM parameters that used in the simulation. The DC-link voltage of inverter 1 and inverter 2 are identically 150 V, and the control period is 50 us. The reference torque is changed from 15% to 40% of rated electromagnetic torque, and the constant speed load rotates as 1000 rpm. The subdividing constant is applied as 4, and weighting factors for stator linkage flux and electromagnetic torque have 120:1 ratio which considered by rated value in Table III.

Fig. 6 and Fig. 7 represent the simulation results of the stator currents of each phase (i_{abc}), the electromagnetic torque (T_e) and its reference (T^*_e), and the minimum value

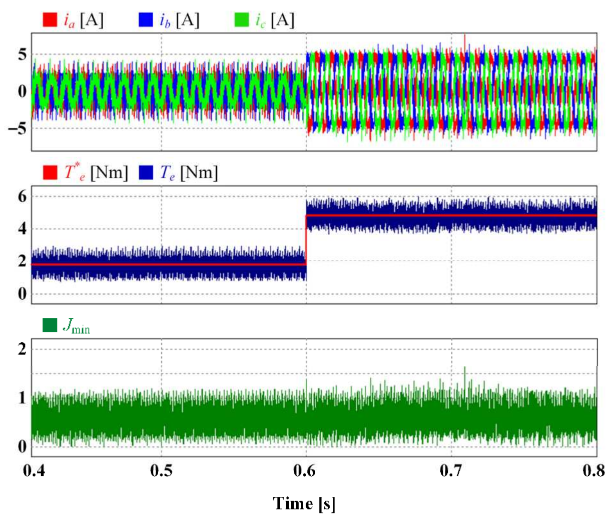

Fig. 6. Simulation results for C-PTC method (1000 rpm).

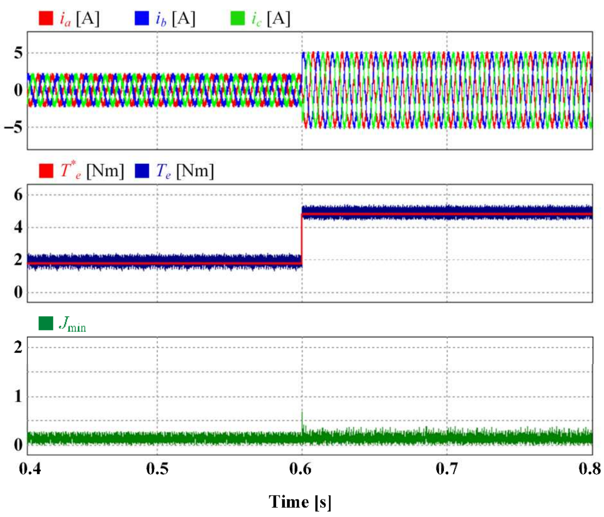

Fig. 7. Simulation results for proposed DB-PTC with SVM method (1000 rpm).

of the cost function (J_{min}). Fig. 6 and Fig 7 show the simulation results for the C-PTC method, and the proposed DB-PTC with SVM method, respectively. The electromagnetic torque ripple affects on stator currents quality and has decreased in the proposed DB-PTC with SVM method compared to the C-PTC method. The total harmonic distortion (THD) in the C-PTC method is 26.44%, and in the proposed DB-PTC with SVM method is 8.33%. The minimum value of cost function means how the reference voltage vector is optimal for following reference values. If the cost function value is 0, it means the most optimal value is selected. In C-PTC method, the minimum value of cost function's average is 0.67, but in the proposed DB-PTC with SVM method is 0.15. The proposed DB-PTC with SVM method shows about four times better performance for selection of reference voltage vector compared to the C-PTC method.

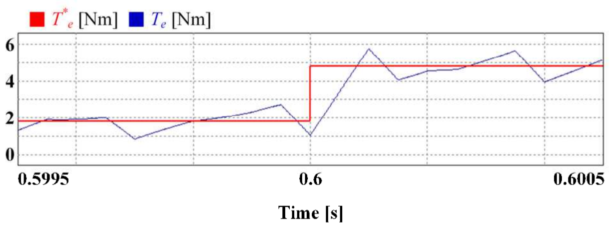

Fig. 8. Simulation results for C-PTC method in transient state (1000 rpm).

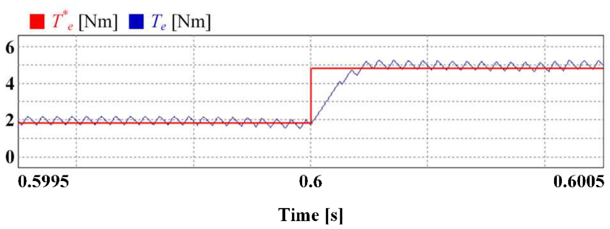

Fig. 9. Simulation results for proposed DB-PTC with SVM method in transient state (1000 rpm).

Fig. 8 and Fig. 9 represent the transient state of the electromagnetic torque in the Fig. 6 and Fig. 7 as magnified waveforms. Fig. 8 shows transient time in the C-PTC method, and it takes about 78.54 us. Fig. 9 shows transient time in the proposed DB-PTC with SVM method, and it takes about 85.66 us. The transient time increased by about 7.12 us, and both times are within two control periods. Therefore, the proposed DB-PTC with SVM method takes longer transient time compared to the C-PTC method, but it's not affected enough to exceed one control period.

VI. Conclusions

In this paper, the DB-PTC with SVM method was proposed for improving the steady state by decreasing torque ripple when driving OEW-IPMSM fed by the dual inverter. The C-PTC method can be applied the voltage vectors on the real switching states. Accordingly, the C-PTC method has large ripples on the torque or stator currents and has irregular switching frequency. However, in the proposed DB-PTC with SVM method, the deadbeat method enables determining the specific voltage vector generation region in two steps to select more optimal reference voltage vector. The number of calculations was reduced, so calculation burden to microprocessor would be decreased. The error between the electromagnetic torque and the reference value was decreased, and THDs in stator currents were also decreased significantly. In addition, the proposed DB-PTC with SVM method offered good performance in steady state as good as generally used PI controllers. PI controllers has trade-off between transient state and steady state by the bandwidth, and thus problems such as overshoot may occur in transient state. The transient time was slightly increased compared to the C-PTC method, but it's not affect enough to get worse in performance. The validity of the proposed DB-PTC with SVM method was confirmed by the simulation results compared with the C-PTC method.

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