Torque Predictive Control for Permanent Magnet Synchronous Motor Drives Using Indirect Matrix Converter

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Abstract

This paper presents an improved torque predictive control (TPC) for permanent magnet synchronous motors (PMSMs) using an indirect matrix converter (IMC). The IMC has characteristics such as a high power density and sinusoidal waveforms of the input-output currents. Additionally, this configuration does not have any DC-link capacitors. Due to these advantages of the IMC, it is used in various application fields such as electric vehicles and railway cars. Recently, research on various torque control methods for PMSM drives using an IMC is being actively pursued. In this paper, an improved TPC method for PMSM drives using an IMC is proposed. In the improved TPC method, the magnitudes of the voltage vectors applied to control the torque and flux of the PMSM are adjusted depending on the PMSM torque control such as the steady state and transient response. Therefore, it is able to reduce the ripples of the output current and torque in the low-speed and high-speed load ranges. Additionally, the improved TPC can improve the dynamic torque response when compared with the conventional TPC. The effectiveness of the improved TPC method is verified by experimental results.

Key words: Current source rectifier, Indirect matrix converter, Permanent magnet synchronous motor, Torque predictive control, Voltage source inverter

I. INTRODUCTION

Recently, interest in renewable energy systems such as wind power generation, hydroelectric power generation, and bioenergy has increased due to the depletion of fossil fuels. In renewable energy systems, a power conversion system is required to transmit the power generated by the renewable energy sources to the grid. In general, power conversion systems, such as in AC-DC-AC power conversion systems, are composed of three stages. The three stages are a rectifier stage, a DC-link, and an inverter stage. However, in the proposed system, electrolytic capacitors with a large volume are used in the DC-link for the AC-DC-AC power conversion [1]. Since electrolytic capacitors increase the volume of the system, AC-DC-AC power conversion systems are used in restricted applications. In addition, electrolytic capacitors shorten the lifetime of the system. These drawbacks can be overcome using an indirect matrix converter (IMC) [2]-[4]. IMCs do not have electrolytic capacitors in the DC-link [5]-[8]. They can overcome the disadvantages of large electrolytic capacitors in general AC-DC-AC power conversion systems. In addition, IMCs have high power density and sinusoidal input-output current characteristics [9]. Therefore, IMCs can be used in various application fields such as electric vehicles and railway cars. Various torque control methods including direct torque control (DTC) and torque predictive control (TPC) with permanent magnet synchronous motor (PMSM) drives using an IMC are being actively studied [10]-[13].

DTC as a torque control method that uses a hysteresis controller with a look-up table. It has advantages such as a simple structure in terms of the system design and fast torque response characteristics [14]. However, in DTC, because the voltage vector is always fixed by a look-up table in a given control period, the ripple components of the current and...
torque of PMSMs are increased [15]-[18]. Unlike DTC, TPC uses voltage vectors calculated based on the relations among the torque, flux and voltage [19], [20]. TPC also has a simple controller configuration and a fast dynamic torque response. In TPC, the ripple components of the current and torque are also increased [21], [22].

An improved TPC method for PMSM drives using an IMC is proposed in this paper. Using the proposed control method, the ripple components of the current and torque of a PMSM are decreased and the dynamic torque response can be enhanced when compared with the conventional TPC. The effectiveness of the improved TPC method is verified by experimental results.

II. TOPOLOGY AND MODULATION METHOD OF AN IMC

A. Topology of an IMC

Fig. 1 shows the circuit configuration of an IMC for PMSM drives. The IMC consists of three stages: input stage with an AC source and an L–C filter, power-conversion stage with power semiconductor switches, and output stage with the PMSM. The L–C filter, which is composed of inductors (L) and capacitors (C) in the input stage, is used to improve the quality of the voltages and currents generated by the AC source. The IMC, the power conversion stage, consists of two sub-stages. These stages are a current source rectifier (CSR) stage and a voltage source inverter (VSI) stage. Since the IMC does not have DC-link capacitors, they are directly connected by a hypothetical DC-link. The PMSM can be controlled by the IMC.

B. Modulation Method of the CSR Stage

By using modulation of the CSR stage, the maximum voltage of the AC source can be transferred to the DC-link. This technique guarantees the sinusoidal currents and unity power factor of the input stage. Fig. 2 shows a space vector diagram of the CSR stage with the voltage vector and current vector located in sector 1. In the space vector diagram shown in Fig. 2, \( \theta_U \) is the phase angle of the current vector, and \( \phi_U \) is the phase angle between the voltage vector and the current vector. The space vector of the CSR stage is categorized by two kinds of states, i.e., three null states and six active states. The three null states occur when the upper and lower switches

\[
\cos \theta_U + \cos \theta_V + \cos \theta_W = 0, -\frac{\cos \theta_U}{\cos \theta_V} \cdot \frac{\cos \theta_W}{\cos \theta_U} = 1
\]

\[
d_x = -\frac{\cos \theta_U}{\cos \theta_U}, d_y = -\frac{\cos \theta_V}{\cos \theta_U}
\]

The average value of the hypothetical DC-link voltage \( V_{DC-av} \) modulated by the CSR stage is calculated using the line-to-line voltage, \( d_x \) and \( d_y \). \( V_{DC-av} \) is expressed as:

\[
V_{DC-av} = d_x V_{UV} - d_y V_{UV_W}
\]

where \( V_{UV} \) is the line-to-line voltage between the U-phase and the V-phase; and \( V_{UV_W} \) is the line-to-line voltage between the W-phase and the U-phase. Finally, \( V_{DC-av} \) is calculated in (4) by substituting \( d_x \) and \( d_y \) from (2) into \( V_{DC-av} \), which is given in (3).

\[
V_{DC-av} = \frac{3}{2} \cdot \frac{V_{UV}}{\cos \theta_U} \cdot \cos \phi \left( \frac{\pi}{6} \leq \theta_U, \phi \leq \frac{\pi}{6} \right)
\]
where $v_m$ is the amplitude of the voltage vector. The other five sectors have the same interpretations. The switching states and $V_{DC-av}$, based on the six sectors in the space vector diagram of the CSR stage, are presented in Table I.

### C. Modulation Method of the VSI Stage

The modulation method for the VSI stage is the same as that of a common inverter. Fig. 3 shows a space vector diagram of the VSI stage. The space vector of the VSI stage is composed of six active vectors ($V_1-V_6$) and two zero vectors ($V_0$ and $V_7$). The active vectors are able to apply the effective voltage to the load, and the amplitudes of the active vectors are equal to 0.667 times $V_{DC-av}$. On the other hand, the zero vectors cannot apply the effective voltage to the load. They are produced by turning ON the three upper ($S_{up}$, $S_{bp}$, $S_{cp}$) or the three lower switches ($S_{lo}$, $S_{bn}$, $S_{cn}$) of the VSI stage.

Additionally, the modulation signals ($v_{A-low}$ and $v_{A-up}$) for the VSI stage, using the space vector modulation method for the $A$ phase, can be expressed as:

$$v_{A-low} = 2d_s \cdot \frac{v_A - 0.5(v_{A(\text{MAX})} + v_{A(\text{MIN})})}{V_{DC-av}} - d_s,$$

$$v_{A-up} = -2d_s \cdot \frac{v_A - 0.5(v_{A(\text{MAX})} + v_{A(\text{MIN})})}{V_{DC-av}} + d_s,$$

where $v_A$ is the reference voltage amplitude of the $A$ phase, and $v_{A(\text{MAX})}$ and $v_{A(\text{MIN})}$ are the maximum and minimum values of the reference voltage in the $A$ phase, respectively.

### III. TORQUE PREDICTIVE CONTROL METHOD

#### A. Conventional TPC

In the conventional TPC method, the voltage vectors required for the control of the torque of the PMSM are calculated using the relations among the torque, the flux, and the voltage equation. Fig. 4 shows a space vector diagram of the PMSM in different coordinate axes. $d^x-q^y$ and $d^x-q^y$ are the stationary and rotating reference frames synchronized to the PMSM rotor, respectively. $\theta_s$ and $\theta_r$ indicate the phase angles of the stator flux vector ($\psi_s$) and the rotor flux vector ($\psi_r$), respectively. $\alpha$ is the phase angle between $\psi_r$ and the voltage vector ($v_s$), $\beta$ is the phase angle between $\psi_r$ and the stator flux ($\psi_s$).

The electromagnetic torque is expressed using $\bar{\psi}_r$ and the stator current vector ($\bar{\bar{i}}_s$) as:

$$T_e = \frac{3}{2} \frac{P}{(\bar{\psi}_r \times \bar{\bar{i}}_s)},$$

where $P$ is the number of poles of the PMSM. In addition, the rate of change of the PMSM torque ($T_e$) is expressed as:

$$\frac{dT_e}{dt} = \frac{3}{2} \frac{P}{(\bar{\psi}_r \times \bar{\bar{i}}_s + \bar{\psi}_r \times \bar{\bar{i}}_s)} (\frac{d\bar{\psi}_r}{dt})$$

The voltage vector in the $d^x-q^y$ stationary reference frame can be expressed as:

$$\bar{v}_s = R_s \bar{\bar{i}}_s + \frac{d\bar{\psi}_r}{dt},$$

where $\bar{\bar{i}}_s$ is the stator current vector, and $R_s$ is the stator resistance of the PMSM [23]-[29]. The rate of change of $\bar{\psi}_r$ is expressed in (9), based on (8).

$$\frac{d\bar{\psi}_r}{dt} = v_r - R_s \bar{\bar{i}}_s,$$

In (9), the stator flux vector $\bar{\bar{\psi}}_s$, can be expressed as:

$$\bar{\bar{\psi}}_s = L_s \bar{\bar{i}}_s + \bar{\psi}_r,$$
where $L_s$ is the stator self-inductance. The rate of the change of $\dot{i}_s$ is expressed in (11), based on (10).

$$\frac{d\dot{i}_s}{dt} = \frac{1}{L_s} \left( \frac{d\bar{v}_r}{dt} - \frac{d\bar{\psi}_e}{dt} \right).$$  \hspace{1cm} (11)

Finally, the rate of the change of $T_e$, as given in (7), can be rewritten as in (12) by substituting (9) and (11) into (7).

$$\frac{dT_e}{dt} = \frac{3P}{4L_s} \left[ \left(\bar{v}_r \times \dot{i}_s\right)T_e + \left(\frac{4R}{3P}T_e + \bar{\psi}_r \times \frac{d\bar{\psi}_e}{dt}\right)T_e \right],$$  \hspace{1cm} (12)

From (12), the rate of the change of $T_e$ can be controlled by the voltage vector $\bar{v}_r$, which is calculated based on $\dot{i}_s$, $\bar{\psi}_r$, and $\bar{\psi}_e$. Based on the application time of $\bar{v}_r$ to control the PMSM torque during a control period, the changing rate of $T_e$, as given in (12), can be expressed as:

$$\Delta T_e = \frac{3P}{4L_s} \left[ \left(\bar{\psi}_r \times \bar{v}_r\right)T_e - \left(\frac{4R}{3P}T_e + \bar{\psi}_r \times \frac{d\bar{\psi}_e}{dt}\right)T_e \right].$$  \hspace{1cm} (13)

where $T_c$ is the control period, and $T_d$ is the duration of $\bar{v}_r$.

From (13), $\alpha$, the phase angle between $\bar{v}_r$ and $\bar{\psi}_r$, can expressed as:

$$\alpha = \sin^{-1} \frac{4R}{3P} \bar{\psi}_r \bar{v}_r T_e.$$  \hspace{1cm} (14)

**B. Improved TPC**

In the TPC method, the voltage vector magnitude is determined by multiplying the maximum magnitude of $\bar{v}_r$, by a constant ($e$), which is determined to have a value between 0 and 1. In conventional TPC methods, $e$ is fixed at 0.7 or 1 since these values enhance the transient response of the PMSM torque control. However, in the steady state, these values result in an unnecessarily long application time of $\bar{v}_r$. Based on this unnecessary application time of $\bar{v}_r$, the ripple components of the current and torque in the PMSM are increased.

Therefore, in this paper, the improved TPC method is used to decrease the ripple components of the current and torque in a PMSM. Fig. 5 shows the determination of $e$ in the steady state and the transient state with the improved TPC method. In the improved TPC method, $e$ is not fixed at 0.7 or 1. Instead, it is appropriately determined as the value that decreases the unnecessary application time of $\bar{v}_r$ in the steady state. In other words, in the steady state, $e$ is determined to be the value that minimizes the magnitude of the voltage vector, which is required for PMSM torque control. Therefore, with an appropriate value of $e$, the ripple components of the current and torque in the PMSM can be decreased. Additionally, in the transient state, $e$ is set to a value that improves the transient response of the torque control.

Fig. 6 shows the modified voltage vector ($\bar{v}_r^{mod}$) for decreasing the ripple components of the current and torque in the PMSM. $\bar{v}_r^*$ is the reference voltage vector, and $\alpha^*$ and $\alpha^{**}$ are the phase angles of $\bar{v}_r^*$ and $\bar{v}_r^{mod}$, respectively. $\bar{v}_r^{mod}$ is obtained from the magnitude and phase angle of $\bar{v}_r^{mod}$, which is described below.

In (9), the voltage drop due to the stator resistance can be ignored since it is negligibly small when compared with the rate of the change of $\bar{\psi}_r$. Therefore, the rate of the change of $\bar{\psi}_r$ is rewritten as in (15). From (15), the magnitude of $\bar{\psi}_r$ in the stator reference frame can be calculated using the rate of the change of $\bar{\psi}_r$.

$$\frac{d\bar{\psi}_r}{dt} = \bar{v}_r - R_s \dot{i}_s, \hspace{1cm} \Delta \bar{\psi}_r = \bar{v}_r T_e, \hspace{1cm} \bar{v}_r = \Delta \bar{\psi}_r T_e^{-1}. \hspace{1cm} (15)$$
Finally, the magnitude of $\overrightarrow{\gamma_{\text{mod}}}$ can be calculated via $\alpha^*$, which is the phase angle of $\overrightarrow{\gamma}$ obtained from (14), and the magnitude of $\overrightarrow{\gamma}$ obtained from (15). In addition, the appropriate value of $e$ that decreases the ripple components of the current and torque in the steady state or improves the transient response of the torque control in the PMSM is determined as:

$$e = \frac{\|\overrightarrow{\gamma_{\text{mod}}}\|}{\|\overrightarrow{\gamma}\|} = \sqrt{(\Delta\psi_T)^2 + (\overrightarrow{\gamma}_{\sin \alpha})^2} / \|\overrightarrow{\gamma}\|$$  \hspace{1cm} (16)

$\alpha^*$ as the phase angle of $\overrightarrow{\gamma_{\text{mod}}}$, is expressed as in (17) using (14) and (16).

$$\alpha^* = \sin^{-1}\left(\frac{1}{e} \sin \alpha\right)$$  \hspace{1cm} (17)

C. Control Method for PMSM Drives Using an IMC

Fig. 7 shows a control block diagram for PMSM drives using an IMC with the improved TPC method. Fig. 8 shows the control block diagram for PMSM drives using an IMC with the improved TPC method. The IMC, which consists of the CSR stage and the VSI stage, is connected to the AC source and the PMSM. The input stage of the IMC has an L–C filter with values of $L_v$ and $C_v$. The L–C filter is able to reduce the ripple components of the currents supplied by the grid into the PMSM.

In Fig. 7, the three-phase currents ($I_u, I_v,$ and $I_w$) of the input stage are transformed to the $d$-$q$ axes using the phase angle ($\theta$) of the AC source. Through the modulation method of the CSR stage and the $d$-$q$ axes currents, the duty ratios $d_d$ and $d_q$ are calculated. Additionally, the average value of the hypothetical DC-link voltage $V_{\text{DC-av}}$ is calculated based on $d_d$, $d_q$, and the line-to-line voltages. The three-phase currents ($I_u, I_v,$ and $I_w$) of the output stage are transformed to the $d$-$q$ axes using the phase angle ($\theta$) of the PMSM rotor. In addition, $T_e$, the PMSM torque, and the stator flux vector $\overrightarrow{\psi_s}$, are calculated as in (6) and (10). The output torque error ($\Delta T_e$) and the stator flux error ($\Delta \psi_s$) are calculated using $T_e$, $\psi_s$, the reference torque ($T_e^*$), and the reference stator flux ($\psi_s^*$). The reference voltage vector ($\overrightarrow{\gamma}$) is calculated via the TPC using $\Delta T_e$ and $\Delta \psi_s$. Additionally, $\overrightarrow{\gamma}$ is modified to $\overrightarrow{\gamma_{\text{mod}}}$ in the improved TPC method. Finally, the VSI stage is modulated by $\overrightarrow{\gamma_{\text{mod}}}$ via the space vector modulation method.

IV. EXPERIMENTAL RESULTS

Experiments were conducted to evaluate the performance of the improved TPC method for PMSM drives using an IMC. Fig. 8 shows the experimental setup. In the control board, a digital signal processor (DSP) using a TMS320C28346 is used to program the improved TPC method. The power supplied by the grid is transmitted to the PMSM by the IGBTs in both the CSR stage and the VSI stage. In addition, the parameters of the PMSM and sampling time for the control scheme are presented in Table II.

Fig. 9 shows experimental results in terms of the input line-to-line voltage ($V_{uv}$), the average value of the hypothetical DC-link voltage ($V_{\text{DC-av}}$), and the DC-link voltage ($V_{DC}$) of the IMC with a 5 N·m output torque and a load at 300 rpm. $V_{uv}$ is provided by the AC source. $V_{\text{DC-av}}$ can be calculated using $d_d$ and $d_q$ as the duty ratios. $V_{DC}$ is generated by the modulation of the CSR stage.

Fig. 10 shows experimental results of the output torque ($T_e$) and stator flux ($\psi_s$) in the steady state. $T_e$ and $\psi_s$ are set to the reference values of 5 N·m and 0.55 Wb, respectively. The control method is switched to the improved TPC method from the conventional TPC method at 0.5 s. Comparing the performance of the conventional TPC and the improved TPC
in the steady state, the ripple component of the output torque is decreased from 0.4 N·m to 0.2 N·m. In addition, the ripple component of the stator flux ($\psi_s$) is decreased from 0.04 Wb to 0.015 Wb.

Figs. 11(a) and 11(b) show experimental results of the dynamic torque response. The reference torque is changed from 5 N·m to 10 N·m at 0.5 s. In addition, Figs. 11(a) and 11(b) show an expanded waveform of the torque. Comparing the dynamic torque response between the conventional TPC and the improved TPC, the response time is decreased from 0.5 ms to 0.3 ms.

V. CONCLUSIONS

This paper presents an improved TPC method for PMSM drives using an IMC. The IMC method for the control of a PMSM uses no electrolytic capacitors in the DC link. In addition, it has high power density and sinusoidal waveforms in the input-output current. In general, existing torque control methods including DTC and TPC are applied to control PMSMs. However, DTC and the conventional TPC result in ripple components in the current and torque in the PMSM. Therefore, in this paper, the improved TPC for PMSM drives using an IMC is proposed. The improved TPC decreases the ripple components of the current and torque in the PMSM. In addition, this method improves the characteristics of the dynamic torque response. Additionally, since the magnitudes of the applied voltage vectors are adjusted depending on the PMSM torque control such as the steady state and transient response in the improved TPC method, the switching loss of the improved TPC method are similar to that of the conventional TPC method. The effectiveness of the proposed control method is verified by experimental results.

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