A New Scheme to Direct Torque Control of Interior Permanent Magnet Synchronous Machine Drives for Constant Inverter Switching Frequency and Low Torque Ripple

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Received: January 07, 2012 / Accepted: March 19, 2012 / Published: December 31, 2012.

Abstract: DTC (direct torque control) can produce quick and robust response, but it has the problems of large torque ripples and inconstant inverter switching frequency. This paper introduces a modified direct torque control based on the SVM (space vector modulation) for IPMSM (interior permanent magnet synchronous motor) drive. Two PI (proportional-integral) controllers regulate the flux and torque, respectively, and the inverter is controlled by the SVM technique in the proposed DTC system. Simulation results show that the performance of the proposed DTC system has been improved with respect to the conventional DTC. The DTC system can effectively reduce the flux and torque ripples.

Key words: Direct torque control, permanent magnet synchronous machine, space vector modulation.

1. Introduction

PMSM (permanent magnet synchronous motors) are used in many applications that require rapid torque response and high-performance operation. The torque in PMSM’s is usually controlled by controlling the armature current based on the fact that the electromagnetic torque is proportional to the armature current. For high performance, the current control is normally executed in the rotor (d-q) reference frame that rotates with the synchronous speed. In this frame, the armature inductances and magnet flux linkage are constant if the back EMF (electromotive force) and variation of inductances are sinusoidal. In addition to the influence of the harmonic terms in inductances and back EMF, saturation in flux and temperature effect on the magnet, the torque response under current control is limited by the time constant of the armature winding. Since DTC (direct torque control) was proposed in the middle of 1980s, the DTC principle has been widely used for induction motor drive [1-4]. The basic principle of DTC is to directly select stator voltage vector according to the differences between the references of torque and stator flux linkage and their actual values. Compared with vector control, the DTC has many advantages such as less machine parameter dependence, simpler implantation and quicker dynamic torque response. The principle has also been applied to the IPMSM (interior permanent magnet synchronous motor) [5-9]. Although DTC has many advantages over vector control, it still has some drawbacks. Due to the torque and flux hysteresis controllers, the conventional DTC has large torque and flux ripples, which deteriorate the control system performance, especially at the low speed. Moreover, the inverter does not have constant...
switching frequency. To solve the problems of large torque ripple and inconstant inverter switching frequency in the conventional DTC, many researchers have given attention to these problems [10].

To improve the performance of the classical DTC, there exist different solutions. The first category is hardware related, by using multiple level inverters, more control voltage space vectors can be generated to reduce torque and flux ripples. With more power switches needed, the system cost and complexity increase. Refs. [11, 12] have presented superimposing a high-frequency and small amplitude triangular dither signal on the flux and torque errors to counteract the delay time in the feedback signals. With the help of extra hardware, this method is simple to implement and can achieve faster switching frequency in the DTC controller. Attempts to improve the switching table were made in second category. However, experimental results show no significant improvement on reduction of the torque and flux ripples. Mir et al. proposed fuzzy logic based DTC for improving the performance of the classical DTC. Fast torque dynamic was reported in computer modeling, however, experimental verification was not given.

In this paper, a new scheme DTC method for IPMSM is presented based on SVM techniques. The speed controller is a classical PI (proportional-integral) regulator, which produces the reference torque. The calculated flux and torque are compared with the reference flux and torque. Two PI controllers regulate the flux and torque, respectively. Then the inverter is controlled by the SVM (space vector modulation). This scheme features low flux and torque ripples and fixed switching frequency. The block diagram of the proposed IPMSM DTC is given in Section 3. Section 2 introduced the machine model in the stator flux reference frame. Simulation results in Section 4 show that the proposed DTC method for IPMSM can reduce the flux and torque ripples and improve the performance of control system.

2. Motor Equations in the Stator Flux Reference Frame

The stator flux linkage vector \( \psi_s \), and rotor (magnet) flux linkage vector \( \psi_f \) can be drawn in the rotor flux (d-q), stator flux (x-y), and stationary (D-Q) reference frames, as shown in Fig. 1. The angle between the stator and rotor flux linkages \( \delta \) is the load angle when the stator resistance is neglected. In the steady state \( \delta \) is constantly corresponding to a load torque, and both stator and rotor flux rotate at the synchronous speed. In transient operation, \( \delta \) varies and the stator and rotor flux rotate at different speeds. Since the electrical time constant is normally much smaller than the mechanical time constant, the rotating speed of stator flux with respect to the rotor flux can be easily changed. It is shown in this section that the increase of torque can be controlled by controlling the change of \( \delta \) or the rotating speed of the stator flux. The well-known stator flux linkage, voltage, and electromagnetic torque equations in the dq reference frame are as follows:

\[
\begin{align*}
\psi_d &= L_d i_d + \psi_f \\
\psi_q &= L_q i_q \\
\nu_d &= R_i i_d + p \psi_d - \omega \psi_q \\
\nu_q &= R_i i_q + p \psi_q + \omega \psi_d \\
T &= \frac{3}{2} p (\psi_d i_q - \psi_q i_d)
\end{align*}
\]

where \( \psi_f \), \( L_d \) and \( L_q \) are the armature (or stator) back EMF constant and inductances, respectively, when the back EMF and the variation of the stator inductances are sinusoidal. Otherwise, these are the fundamental quantities of these variables. With the transformation in Eq. (4), Eqs. (1)-(3) can be transformed to the xy reference frame:

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} =
\begin{bmatrix}
\cos \delta & -\sin \delta \\
\sin \delta & \cos \delta
\end{bmatrix}
\begin{bmatrix}
F_d \\
F_q
\end{bmatrix}
\]

2.1 The Torque Equation in xy Reference Frames

From Fig. 1, it can be found that:

\[
\begin{align*}
\sin \delta &= \frac{\psi_q}{|\psi_f|} \\
\cos \delta &= \frac{\psi_d}{|\psi_f|}
\end{align*}
\]
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where $|\varphi_s|$ represents the amplitude of the stator flux linkage. Substituting Eqs. (5) and (6) for current into Eq. (2) gives:

$$
\begin{bmatrix}
\varphi_s \\
\varphi_f
\end{bmatrix} =
\begin{bmatrix}
L_d & 0 & i_d \\
0 & L_q & i_q
\end{bmatrix}
+ \begin{bmatrix}
\varphi_f \\
\varphi_f
\end{bmatrix}
$$

(7)

Eq. (7) means that the torque is directly proportional to the axis component of the stator current if the amplitude of the stator flux linkage is constant.

2.2 The Flux Linkage Equations in the Reference Frame

Eq. (3) can be rewritten into matrix form as follows:

$$
\begin{bmatrix}
\varphi_d \\
\varphi_q
\end{bmatrix} =
\begin{bmatrix}
L_d & 0 & i_d \\
0 & L_q & i_q
\end{bmatrix}
+ \begin{bmatrix}
\varphi_f \\
\varphi_f
\end{bmatrix}
$$

(8)

Substituting Eq. (5) into Eq. (8) gives:

$$
\begin{bmatrix}
\varphi_d \\
\varphi_q
\end{bmatrix} =
\begin{bmatrix}
L_d \cos \delta & L_d \sin \delta & \cos \delta & -\cos \delta & i_d \\
-L_q \sin \delta & L_q \cos \delta & \sin \delta & -\sin \delta & i_q
\end{bmatrix}
+ \begin{bmatrix}
\varphi_f \\
\varphi_f
\end{bmatrix}
$$

(9)

For a PMSM with pole saliency, that is, $L_d \neq L_q$ the torque equation in terms of stator flux linkage and load angle can be obtained by solving $i_d$ and $i_q$ from Eq. (9), with $\varphi_y = 0$ as follows [5]:

$$
T = \frac{3p\varphi_y}{4L_dL_q} \left[ 2\varphi_y L_q \sin \delta - \varphi_y (L_q - L_d) \sin 2\delta \right]
$$

(10)

The voltage equations of the IPMSM in the stator flux reference frame (x-y), which can be derived as:

$$
\begin{align*}
V_x &= R_i i_x + \frac{d\varphi_x}{dt} = R_i i_x + \frac{d\varphi_y}{dt} \\
V_y &= R_i i_y + \omega \varphi_x = R_i i_y + \omega \varphi_y
\end{align*}
$$

(11)

where $R_i$ is the stator armature resistance.

Eq. (11) shows the rotating speed of the stator flux vector which can be controlled by appropriate stator voltage vector. It is obvious that the amplitude of stator flux vector can be regulated by $x$ component of stator voltage directly. And the torque can be indirectly regulated by $y$ component of stator voltage.

It is necessary to discuss the relationship between the amplitude of stator flux linkage and the derivative of the torque. As indicated in Ref. [13], stable torque control can be achieved if:

$$
\varphi_y < \frac{L_q}{L_q - L_d} \varphi_f
$$

(12)

3. Proposed DTC-SVM Scheme

The block diagram of the proposed PMSM DTC drive is shown in Fig. 2. The speed controller is a classical PI (proportional-integral) regulator, which produces the reference torque. The calculated flux and torque are compared with the reference flux and torque. Two PI controllers regulate the flux and torque, respectively. Then the inverter is controlled by the SVM (space vector modulation). A DC bus voltage and two phases current are detected to calculate the stator flux linkage and torque. For the proposed DTC method, the estimation of flux linkage and torque are carried out in the stationary reference frame, as shown in Eqs. (13)-(14):

$$
\varphi_y = \int (v_y - i_y R_i) dt
$$

(13)

$$
T_e = \frac{3p}{2} (\varphi_d i_y - \varphi_y i_x)
$$

(14)

Before using SVM algorithm the voltage vector should be transferred from the stator flux reference frame (x-y) to the stationary frame (d-q). The objective of SVM (space vector modulation) technique is to approximate the reference voltage instantaneously by combination of switching states corresponding to the basic space vectors. At any time, the stator voltage vector always lies in one of the six sectors, as shown in Fig. 3. For any small period of time, the stator voltage vector can be formed by the combination of adjacent basic space vectors. Suppose that the reference voltage
vector lies in the north sectors, the respective durations of switching states corresponding to adjacent vectors $V_N$, $V_{N+1}$ and the zero vectors $V_0$, $V_7$ are shown in Eqs. (15)-(18).

\[ \gamma = \theta - \frac{(N - 1)\pi}{3}, \quad 0 \leq \gamma < \frac{\pi}{3} \] (15)

\[ T_N = T_p \frac{2U_s}{3V_{dc}} \sin \left( \frac{\pi}{3} - \gamma \right) \] (16)

\[ T_{N+1} = T_p \frac{2U_s}{3V_{dc}} \sin \gamma \] (17)

\[ T_0 = T_s = \frac{T_p - T_N - T_{N+1}}{2} \] (18)

At any period $T_p$, the applied sequence of adjacent vectors $V_N$, $V_{N+1}$ and the zero vectors $V_0$, $V_7$ are $V_0$-$V_N$-$V_{N+1}$-$V_7$-$V_{N+1}$-$V_N$-$V_0$, and the respective durations are $T_0/2$-$T_N/2$-$T_{N+1}/2$-$T_7/2$-$T_{N+1}/2$-$T_N/2$-$T_0/2$ as shown in Fig. 4.

It is well known that for conventional DTC approach, no inverter leg changes switching state during a sampling period. Due to this fact, the inverter switching frequency is less than that of sampling frequency and the associated torque ripple is also significant for low sampling frequency control. To increase the inverter switching frequency for the same sampling frequency, the symmetrical regular-sampled SVM technique with switching patterns as shown in Fig. 4 is used for inverter control of the new DTC-based drive. The inverter switching frequency is constant and equal to sampling frequency. Therefore, for the same sampling frequency, in comparison with the conventional switching-table-based DTC drive, the new DTC-based drive dramatically increases the inverter switching frequency and thereby significantly reduces the torque ripple.

4. Simulation Results

To study the performance of the proposed modified DTC of PMSM drive, two MATLAB/Simulink models were developed. One is used for the conventional DTC and the other for the proposed DTC. The parameters of IPMSM are shown in Table 1.

In Figs. 5 and 6, the steady-state performances of the basic and modified DTC at 1,200 rpm are compared under the same operating condition. As indicated in
Table 1  Parameters of IPMSM machine.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pole pairs ($P$)</td>
<td>2</td>
</tr>
<tr>
<td>Stator resistance ($R$)</td>
<td>5.8 Ω</td>
</tr>
<tr>
<td>Magnet flux linkage ($\phi_f$)</td>
<td>0.533 Wb</td>
</tr>
<tr>
<td>d-axis inductance ($L_d$)</td>
<td>0.0448 H</td>
</tr>
<tr>
<td>q-axis inductance ($L_q$)</td>
<td>0.1024 H</td>
</tr>
<tr>
<td>Phase voltage ($V$)</td>
<td>132 V</td>
</tr>
<tr>
<td>Phase current ($I$)</td>
<td>3 A</td>
</tr>
<tr>
<td>Base speed ($\omega_b$)</td>
<td>1,260 rpm</td>
</tr>
<tr>
<td>Rated torque ($T_b$)</td>
<td>6 Nm</td>
</tr>
</tbody>
</table>

Fig. 5  Stator flux linkage response at 1,200 rpm with 6 Nm load (a) under the conventional IPMSM DTC and (b) proposed IPMSM DTC.

Section 2, stable torque control can be achieved if Eq. (12) is satisfied. Therefore, the selection of rated stator flux linkage is important and in this case $\phi_s = 0.55$ is indicated.

The flux ripple and torque ripple under the basic DTC are 0.03 Wb and 1.5 Nm, respectively. However, the flux and torque ripple under the modified DTC is almost 0.004 Wb and 0.04 Nm. The torque and flux ripples are reduced in the proposed control systems and the performance of the system has been improved. The proposed system is relatively robust with respect to the change of the load torque.

Fig. 6  Torque response at 1,200 rpm with 6 Nm load (a) under the conventional IPMSM DTC and (b) proposed IPMSM DTC.

5. Conclusion

In this paper, a modified direct torque control method for interior permanent magnet synchronous motors is presented based on the voltage space vector modulator. The proposed direct torque control method apparently reduces the torque and flux ripples while preserves the fast response of the conventional DTC.

References


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