A VARIABLE-VOLTAGE DIRECT TORQUE CONTROL BASED ON DSP IN PM SYNCHRONOUS MOTOR DRIVE

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Abstract: In this paper, a kind of variable-voltage direct torque control (DTC) method for permanent magnet synchronous motor (PMSM) drive system is proposed. 24 or more voltage vectors with variable voltage on circle traces are obtained. A new switch table is used to select voltage vectors effectively. By theory analysis and simulation research, the proposed control method is proved to enable diminishing the torque ripple, especially in low speed range. In the preliminary experiment, both smooth control of speed and high dynamic performance are achieved.

Key words: Direct torque control (DTC, DSR), permanent magnet synchronous motor (PMSM), motion control

1. Introduction

In recent years, the motion control system based on DSP-IPM-Motor has become the general mode with the rapid development of computer and power electronics technology. As a control strategy of high dynamic permanence, the direct torque control (DTC) is well fit for digital control in AC servo system because of its less computing and good robust ability. This method has been studied in the control of induction motor [1][2] and put into force in some fields. At the same time, PMSM, with its high power density, high efficiency, high reliance and good dynamic performance, can also be controlled by the DTC, and the good dynamic performance is achieved [3].

In principle, the DTC is not based on the continuous sinusoidal base wave voltage, but discrete voltage vectors in space. Appropriate voltage vectors will be selected discontinuously according to the need of the control of the torque and flux linkage. This control method enables fast dynamic response of the motor. However, because the rotor flux linkage is fixed on the rotor of PMSM, the torque ripple will come up inevitably when making use of voltage vectors discontinuously and the amplitude of the ripple will be larger than the one of the asynchronous motor. So studying the way of minimizing torque ripples is one of the vital problems in direct torque control of PMSM.

In the traditional method of DTC, the voltage is a constant. So it is not easy to control the motor smoothly in low speed range. If the voltage can be adjusted against the speed, the low-speed performance will be improved. A new variable-voltage DTC method for PMSM drive system is proposed based on DSP in the paper. The ripples of the torque and flux linkage are restrained effectively by using the new method.

2. The new control algorithm of DTC in PMSM drive

2.1 Math model of synchronous motor

The stator current, voltage and flux linkage can be drawn in the frame of the stator three-phase (ABC), the stator two-phase (α-β, normally regarding A phase as α *axis*), rotor flux (*d-q*, i.e. rotor frame) and stator flux (*x-y*) reference frames, as shown in Fig.1. In *d-q* frame, L_d, L_q are constant and the stator current is decoupled in the flux (q) and torque (d) direction whether the motor is uniform air gap SM or PMSM with pole saliency.

The equations of the PMSM in *d-q* frame are following:

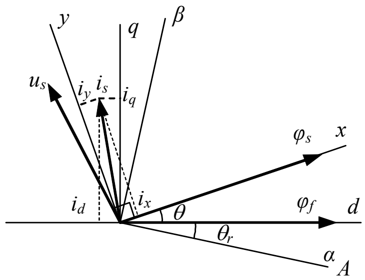

Fig.1 Vectors diagram in different reference frames

$$
\begin{aligned}
u_d &= R_s i_d + p\varphi_d - \omega_r \varphi_q \\
u_q &= R_s i_d + p\varphi_q - \omega_r \varphi_d \\
\varphi_d &= L_d i_d + \varphi_f \\
\varphi_q &= L_q i_q \\
T_e &= p_m |\varphi_s| |\varphi_f| \sin\theta = p_m(\varphi_d i_q - \varphi_q i_d)
\end{aligned} \tag{1}
$$

where u_d, u_q, i_d, i_q are d- and q-axes voltages and currents, respectively; R_s is the stator resistance; φ_d, φ_q are the flux linkage of the stator on d- and q-axes, φ_f is the flux linkage of the rotor; L_d, L_q are d- and q-axes inductions; θ is the angle between the stator and rotor flux linkages, i.e. the torque angle, θ_r represents the angle between the rotor flux linkage and α-axis; p_m is the polar pair.

2.2 Control of the torque and flux linkage

Flux linkage and torque can be calculated according to equation (1) in *d-q* frame. But considering the equation as following:

$$\varphi_s = \int (u_s - R_s i_s) dt \tag{2}$$

It can be calculated in α-β frame, thus the computing quantity and the dependence for the parameters of the motor are decreased. In this way the armature resistance is the only parameter relative to the accuracy of the flux linkage. In Eq.(2) the stator voltage u_s is constant in switching interval, so Eq.(2) can be rewritten as:

$$\varphi_s = u_s t - R_s \int i_s dt + \varphi_s|_{t=0} \tag{3}$$

The method of calculation as follows:

First, transform the three-phase stator currents i_a, i_b, i_c, u_a, u_b, u_c into i_α, i_β, u_α, u_β in α-β frame, and the difference equation of stator flux linkage φ_α, φ_β in Eq.(3) are:

$$
\begin{aligned}
\varphi_\alpha(k) &= \varphi_\alpha(k-1) + (u_\alpha - R_s i_\alpha) T_s \\
\varphi_\beta(k) &= \varphi_\beta(k-1) + (u_\beta - R_s i_\beta) T_s \\
\varphi_s(k) &= \sqrt{\varphi_\alpha^2(k) + \varphi_\beta^2(k)}
\end{aligned} \tag{4}
$$

where T_s represents switching interval.

The parameters in two frames can be transformed with the frame rotating transform where θ is the angle between α-β and *d-q* reference frames. Electro-magnetic torque equation can be got as following:

$$T_e = p_m(\varphi_d i_q - \varphi_q i_d) = p_m(\varphi_\alpha i_\beta - \varphi_\beta i_\alpha) \tag{5}$$

Its discrete form is:

$$T_e(k) = p_m[\varphi_\alpha(k) i_\beta(k) - \varphi_\beta(k) i_\alpha(k)] \tag{6}$$

2.3 Method of subdividing voltage vectors on a circle

Subdivided voltage vectors can be achieved by synthesizing two vectors of the six voltage vectors, as shown in Fig.2. In this way, voltage vectors in all directions will be obtained by adjusting the switch time of each two vectors, and the voltage vectors formed by this means are still on regular hexagon. There are difficulties in the calculation because of the variety of the amplitudes.

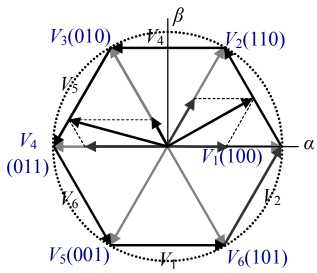

Fig.2 The discreted voltage vectors and their synthesis

It is known that the digital three-phase SPWM generator can provide continuous voltage vectors on a circle in sequence, and the amplitude of these vectors is constant for a given modulation. However in some cases (e.g. the PWM frequency is too high), the interval time of a PWM wave turning on or shutting off is too short for IGBT, as shown in Fig.3a, the right vectors will not be obtained exactly.

Divide the period of PWM triangular wave into some time segment, as shown in Fig. 3, in which voltage vectors may be analyzed respectively. The three-phase voltages of the armatures are in balance if three-phase PWM waves are all '0' or '1', which is called zero voltage. The zero voltage vectors cannot influence the armature currents, flux linkage and torque. Maintaining the effective voltages' operating time, the armature currents will not change whether prolong or shorten the time of the zero voltage vectors, as shown in Fig.3b, c. In other word, it is equivalent to prolong or shorten the turn-on time (or the shut-off time) of the three-phase PWM waves at the same time. It is easy to guaranty each IGBT to turn on or shut off reliably in each PWM period, and the higher control frequency is realizable. Then the reliable three-phase symmetrical PWM waves, i.e. voltage vectors in all directions on a circle can be obtained by this method.

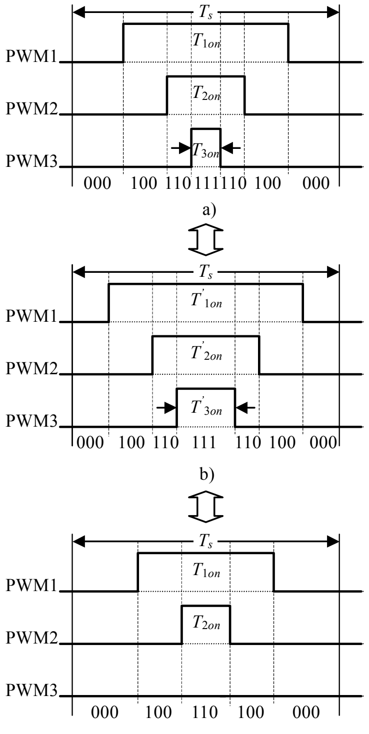

Fig.3 The correction of digital SPWM waves

Moreover, adjusting the modulation can change the amplitude of the voltage vectors generated by SPWM. So the voltage vectors with various amplitudes can be obtained. In the calculation, both the generating and correcting of PWM waves and the 3/2 transforming of voltage vectors can be achieved in the initial program, and will not engross sampling time.

2.4 Switch table

In this paper, voltage vectors are divided in 24directions, and their amplitudes have three degree, as shown in Fig.4. The more voltage vectors make the choice more optimal according to the dispersions of the torque and flux linkage. When the flux linkage is near by V_1, i.e. ±7.5° to V_1, appropriate voltage vectors

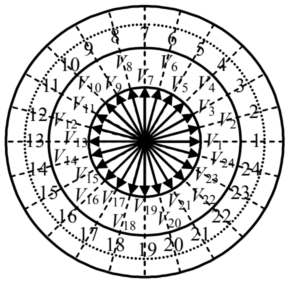
Fig.4 The subdivided voltage vectors

can achieved by the switch table as shown in Table 1 according to τ and ϕ, the errors of the torque and flux linkage, where the values of ϕ *and* τ (−3~+3) represent the degree of the errors between the torque and flux linkage and their given value, from very small to very big. 1~24 represent the 24 voltage vectors, 0 represents 0 voltage vector, I, II, III represent the small, middle, and large voltage respectively. Once the flux linkages of the stator move from zone 1 to zone 2, the sequence numbers of voltage vectors need to plus 1 (except for 0 voltage vector) to obtain appropriate switch voltage vectors. So in this control method, only one switch table is needed.

The values of ϕ *and* τ can be also gained by table. The τ is got by equation as following:

Table 1 Switch table of DTC for PMSM

ϕ \ τ	−3	−2	−1	0	1	2	3
−3	4, III	3, III	2, III	1, III	24, III	23, III	22, III
−2	5, III	4, II	3, II	1, II	23, II	22, II	21, III
−1	6, III	5, II	4, I	1, I	22, I	21, II	20, III
0	7, III	7, II	7, I	0	19, I	19, II	19, III
1	8, III	9, II	10, I	13, I	16, I	17, II	18, III
2	9, III	10, II	11, II	13, II	15, II	16, II	17, III
3	10, III	11, III	12, III	13, III	14, III	15, III	16, III

$$n_\tau = \mathrm{fix}\left(\frac{T_e - T^*}{T_N} K\right) \tag{7}$$

where n_τ is position in the table corresponding to the value of τ, T_N represents rating torque, K is a appropriate coefficient, fix() is a function of integrating. K=T_N can be adapted by $n_\tau = \mathrm{fix}\left(T_e - T^*\right)$ if it can be used for the table.

From all above, it is seen that this control method can be used to DTC control on condition of computing quantity not increased.

3. Implementation of DTC for PMSM drive

The block diagram of a PMSM drive with proposed method may be as shown in Fig.5. The Simulink of

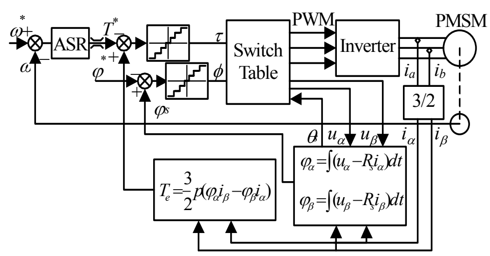

Fig.5 The DTC control system for PMSM

MATLAB is used to test the control method and ability of the switching table for a PMSM. The curves of the flux linkage of the stator and the torque are achieved as shown in Fig.6 and Fig.7 when the sampling frequency is 10KHz. In Fig.6, the ripple of the amplitude of the stator flux linkage is little, and its shape is close to a circle. It can be seen from Fig.7 that the system has a fast torque response. It only spends 220μs to ascend from 0N·m to 4N·m. The torque variation of the motor keep the same speed when the torque changes form 4N·m to −4N·m which takes place at 20ms. Fig.8 is the partly enlarged diagram of Fig.7, which indicates the maximum ripple is only 0.25N·m approximately. For different given torque, it is shown in simulation that the amplitude of the ripple keep constant level.

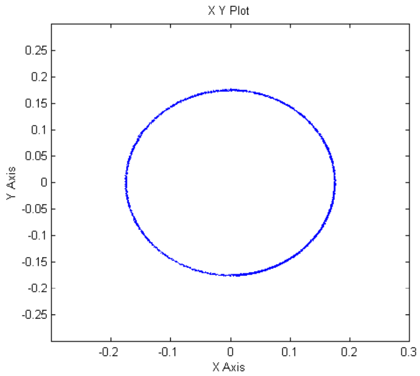

Fig.6 The simulation curve of stator flux

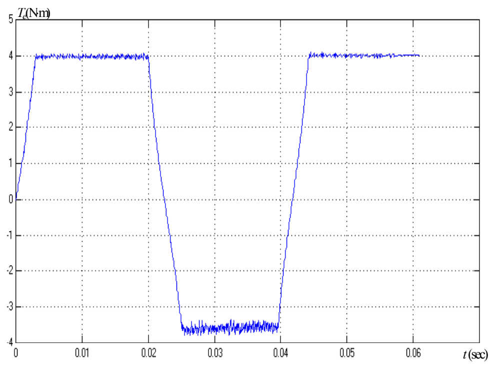

Fig.7 The simulation curve of torque

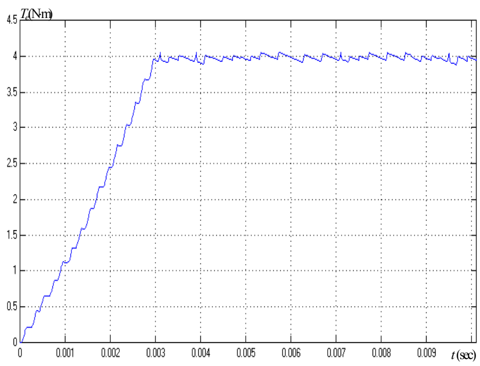

Fig.8 The partly enlarged picture of Fig.7

4. Conclusion

The proposed new method of variable-voltage DTC is used to study the control PMSM based on DSP, and corresponding switch table is bring forward to achieve small torque ripple and high following accuracy of flux linkage with little computing and high sampling frequency. Simulation and preliminary experimental results verify that this method can achieve smooth control effect for the torque and flux linkage, and good dynamic performance.

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