Space Vector Modulated Direct Torque Control for PMSM

YingPei Liu

School of Electrical and Electronic Engineering, North China Electric Power University, Baoding, 071003, China
liuyingpei_123@126.com

Abstract. It always exists that there are big ripples on flux linkage and electromagnet torque in traditional direct torque control (DTC) system. The implement of space vector modulation (SVM) was researched in-depth. The optimum combination of the fundamental voltage space vector was obtained according to the current expected voltage vector so as to compensate the error of stator flux linkage and electromagnet torque in precise. Inverter switch frequency is ensured constant by space voltage vector modulation at the same time. SVM direct torque control for permanent magnet synchronous motor (PMSM) was realized. Simulation results have shown that rapid torque response of DTC is still maintained, ripples on flux linkage and torque are dramatically reduced. The dynamic and static system performances are dramatically improved.

Keywords: Space vector modulation (SVM), Direct torque control (DTC), Permanent magnet synchronous motor (PMSM).

1 Introduction

Permanent magnet synchronous motor (PMSM) has been widely used on a variety of occasions with advantages of high power density and big starting torque and high efficiency. PMSM has become a hot research field of electricity transmission. Direct torque control (DTC) has quick response and good dynamic performance, and it has received extensive attention and made many achievements [1-4].

The output of hysteresis comparator for flux linkage and electromagnet torque can only be 0 or 1, thus, the results can not distinguish the size of error. In a sampling cycle, switching voltage vector selection table can only choose a relatively suitable voltage vector, in most cases, which can not compensate current flux linkage error and electromagnet torque error. Meanwhile, at a fixed sampling period, the inverter switch time can not be controlled under hysteresis comparator, which results in inconstant inverter switch frequency.

Voltage space vector modulation (SVM) DTC for PMSM is researched in-depth in the paper. The excellent dynamic performance of DTC is maintained, and the steady state performance is improved.

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2 Basic Theory of PMSM DTC

The voltage equation of surface PMSM in αβ axis is as following.

$$\begin{cases} u_\alpha = R_s i_\alpha + L_s \dfrac{di_\alpha}{dt} - \omega_r \psi_r \sin\theta_r \\ u_\beta = R_s i_\beta + L_s \dfrac{di_\beta}{dt} + \omega_r \psi_r \cos\theta_r \end{cases} . \tag{1}$$

Where u_α, u_β are the αβ axis components of stator voltage vector; i_α, i_β are the αβ axis components of stator current vector; L_s is the stator inductance; R_s is the stator resistance; ψ_r is permanent magnet flux; ω_r is rotor speed; θ_r is rotor angle.

The torque equation of PMSM is as following.

$$T_e = p_n \left[\frac{\psi_r |\psi_s|}{L_d} \sin\delta_{sm} + \frac{L_d - L_q}{2L_d L_q} |\psi_s|^2 \sin 2\delta_{sm} \right]. \tag{2}$$

Where δ_{sm} is load angle.

If the stator flux amplitude is maintained constant, electromagnet torque can be controlled by controlling load angle, which is the basic theory of DTC.

Fig. 1 shows the diagram of traditional DTC of PMSM. The estimated electromagnet torque value T_e is compared with the given electromagnet torque value T_e^*. The torque control signal ΔT is got by hysteresis comparator of torque. The estimated flux linkage value $|\psi_s|$ is compared with the given flux linkage value $|\psi_s^*|$. The flux linkage control signal $\Delta\psi$ is got by hysteresis comparator of flux linkage. Flux and torque control signals combined with the current position signal $S\psi$, according to switching voltage vector look-up table, the current relative optimal space voltage vector is determined to drive PMSM. The switching voltage vector look-up table is shown in Table 1.

Table 1. Switch Voltage Vector Look-Up Table

$\Delta\psi$	ΔT	①	②	③	④	⑤	⑥
1	1	$\boldsymbol{U}_{s2}$	$\boldsymbol{U}_{s3}$	$\boldsymbol{U}_{s4}$	$\boldsymbol{U}_{s5}$	$\boldsymbol{U}_{s6}$	$\boldsymbol{U}_{s1}$
	−1	$\boldsymbol{U}_{s6}$	$\boldsymbol{U}_{s1}$	$\boldsymbol{U}_{s2}$	$\boldsymbol{U}_{s3}$	$\boldsymbol{U}_{s4}$	$\boldsymbol{U}_{s5}$
−1	1	$\boldsymbol{U}_{s3}$	$\boldsymbol{U}_{s4}$	$\boldsymbol{U}_{s5}$	$\boldsymbol{U}_{s6}$	$\boldsymbol{U}_{s1}$	$\boldsymbol{U}_{s2}$
	−1	$\boldsymbol{U}_{s5}$	$\boldsymbol{U}_{s6}$	$\boldsymbol{U}_{s1}$	$\boldsymbol{U}_{s2}$	$\boldsymbol{U}_{s3}$	$\boldsymbol{U}_{s4}$

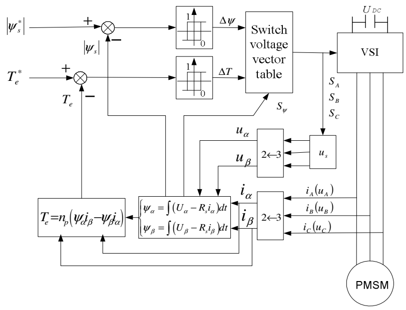


Fig. 1. Diagram of traditional DTC of PMSM

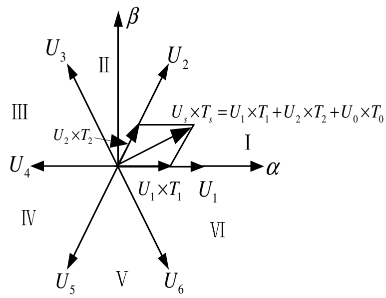


Fig. 2. Diagram of SVM

3 Theory of SVM

The goal of using SVM is to get the required reference voltage space vector by synthesis of the eight basic space vectors inverter generated.

SVM implementation in the first sector is shown as following. The eight basic space vectors are shown in Fig. 2. Eq. 3 can be got by voltage-second relation.

$$\begin{cases} U_s \times T_s = U_1 \times T_1 + U_2 \times T_2 + U_0 \times T_0 \\ T_s = T_1 + T_2 + T_0 \end{cases} . \tag{3}$$

Where Ts is the application time of U_s which is the sample time. T_0、T_1、T_2 is the application time of U_0、U_1、U_2 respectively.

T_1、T_2 can be got from Eq. 3. Also in other sector, T_1、T_2 can be obtained by Eq. 4.

$$\begin{cases} T_1 = T_s \times \dfrac{|U_s|}{|U_1|} \times \dfrac{\sin(60^0 - \varphi)}{\sin 60^0} \\ T_2 = T_s \times \dfrac{|U_s|}{|U_2|} \times \dfrac{\sin\varphi}{\sin 60^0} \end{cases} . \tag{4}$$

Where φ is the angle between the reference voltage vector U_s and the basic voltage vector first implemented. $0 \le \varphi \le 60^0$.

4 Realization of SVM DTC for PMSM

Eq. 5 can be obtained from Eq. 2 by derivation.

$$\frac{dT_e}{dt} = p_n \left[\frac{\psi_r |\psi_s|}{L_d} \cos\delta_{sm} + \frac{L_d - L_q}{2L_d L_q} |\psi_s|^2 \cos 2\delta_{sm} \right] \times \frac{d\delta_{sm}}{dt} . \tag{5}$$

From Eq. 5, it can be seen that the relationship between electromagnet torque change and load angle change is linear. Thus, the PI torque controller can be used to establish the relationship between them.

α, β components of the reference stator flux linkage can be got by Eq. 6. According to the estimated stator flux linkage, the error of flux linkage is shown in Eq.7.

$$\begin{cases} \psi_\alpha^* = |\psi_s^*| \cos(\theta_s + \Delta\delta_{sm}) \\ \psi_\beta^* = |\psi_s^*| \sin(\theta_s + \Delta\delta_{sm}) \end{cases} . \tag{6}$$

$$\begin{cases} d\psi_\alpha = \psi_\alpha^* - \psi_\alpha \\ d\psi_\beta = \psi_\beta^* - \psi_\beta \end{cases} . \tag{7}$$

The expected voltage vector SVM needed is computed by Eq. 8.

$$\begin{cases} U_\alpha = R_s i_\alpha + d\psi_\alpha / T_s \\ U_\beta = R_s i_\beta + d\psi_\beta / T \end{cases} . \tag{8}$$

Schematic diagram of SVM DTC system is shown in Fig. 3. Compared to traditional DTC system, hysteresis comparators of flux linkage and torque are replaced by PI torque controller and the reference flux linkage computation. Switch voltage vector look-up table is replaced by SVM technology.

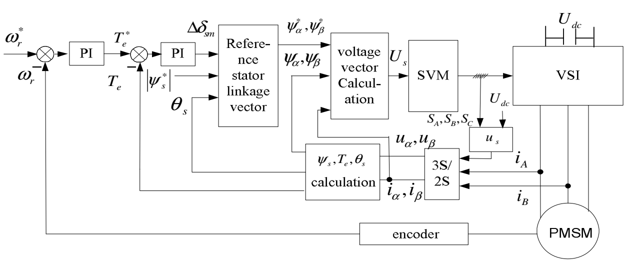
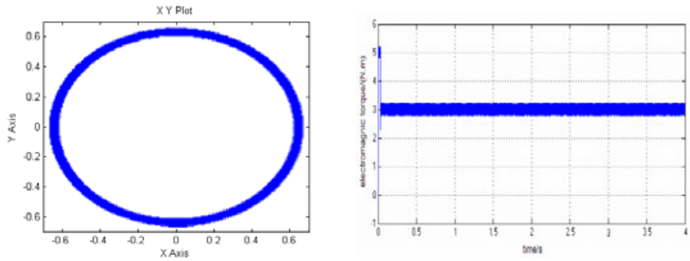


Fig. 3. Schematic diagram of SVM DTC system

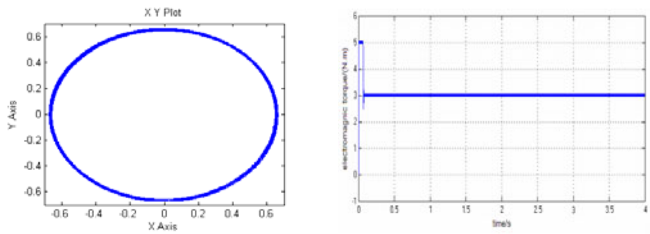
5 Simulation Results

In order to verify the performance of SVM DTC for PMSM, simulation model is built using Matlab/Simulink to carry out simulation.The given speed is 1000r/min and load torque is 5N.m. Flux linkage and electromagnet torque waves is shown in Fig. 4 and Fig. 5 based on traditional DTC and SVM DTC respectively.



(a) Stator flux linkage wave (b) Electromagnet torque wave

Fig. 4. Waves based on traditional DTC method



(a) Stator flux linkage wave (b) Electromagnet torque wave

Fig. 5. Waves based on SVM DTC method

From Fig. 4 and Fig. 5, it can be seen that in the traditional DTC system, there is a big ripple on flux and torque and the waves are not smooth; the flux and torque ripple significantly become lower based on SVM DTC method due to SVM strategy. A precise compensation for flux and torque is achieved. The torque response based on SVM DTC is nearly the same as the traditional DTC method, which indicates the excellent performance of fast response is maintained under SVM DTC method.

6 Conclusion

In order to reduce big ripples of torque and flux in traditional DTC method, SVM DTC for PMSM is researched in the paper to compensate precisely for flux and torque. At the same time, inverter switching frequency is ensured constant. Simulation results have shown that the dynamic and static operating performances of DTC system are improved.

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