Direct Torque Control of Permanent Magnet Synchronous Motor

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Abstract— Due to the features such as high efficiency and high power density Permanent Magnet Synchronous Motors (PMSM) are becoming attractive. In high performance servo applications a rapid and accurate torque control is desired preferably without the use of motion state sensor. The use of PMSM combined with Direct Torque Control (DTC) scheme offers many opportunities to achieve this. This paper describes theoretical aspects of Direct Torque Control for PMSM drives. It is mathematically proven that the increase in electromagnetic torque in a PMSM is proportional to the increase in the angle between stator and rotor flux linkages and therefore fast torque response can be obtained by adjusting the rotating speed of stator flux linkages as fast as possible. It is also shown that zero voltage vectors should not be used and stator flux linkages should be kept moving with respect to rotor flux linkages all the time.

Index Terms— Direct Torque Control, Permanent Magnet Synchronous Motor, Stator flux linkage, Voltage Space Vector.

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1 INTRODUCTION

Direct Torque Control is one of the high performance control strategies designed for AC machines in 1980s. the DTC is implemented by selecting proper voltage space vector (VSV) according to the switching status of the inverter which depends upon the error values between the reference flux linkage and torque with their measured real values obtained from calculations in stationary reference frame by means of simply detecting the motor voltage and currents. The DTC scheme has already been realised successfully in induction motor drives and nowadays for Permanent Magnet Synchronous Motor also [1]. Therefore there are lots of questions and techniques needed to and deserved to be investigated further in this aspect. Aiming at the DTC of PMSM drives this paper illustrates the theoretical basics of DTC in PMSM drives firstly and then explains the application of DTC to PMSM for the purpose of utilizing the successful and matured technique of DTC to solve the problems in implementation of DTC in PMSM.

2. PMSM DRIVE SYSTEM

Following equations are used to derive the mathematical model of PMSM. [4]

$$v_q = R_q\, i_q + \llbracket d\Psi \rrbracket_q/dt + \omega_r\, \Psi_d \tag{1}$$

$$v_d = R_d\, i_d + \llbracket d\Psi \rrbracket_d/dt - \omega_r\, \Psi_q \tag{2}$$

$$\Psi_d = L_d\, i_d + L_m\, i_f \tag{3}$$

$$\Psi_q = L_q\, i_q \tag{4}$$

$$T_e = 2/2\, p[\Psi_f\, i_q + (L_d - L_q) i_q\, i_d] \tag{5}$$

where v_d &v_q are voltages, i_d & i_q are the currents,L_d , L_q& L_m are the inductances, Ψ_d & Ψ_q are the flux linkages of the d and q axes respectively, p is the number of pole pairs , Ψ_f is flux through stator windings and T_e is the electromagnetic torque.

A. Coordinate transformation

Using the coordinate transformation concept, the voltage, flux linkage and current can be transformed from one reference frame to another. Therefore, the torque equation in the synchronous speed reference frame can be written as [5]

$$T_e = \frac{3}{2} p[\Psi_d\big(i_x \sin\delta + i_y \cos\delta\big) - \Psi_q(i_x \cos\delta + i_y \sin\delta)]$$

$$= \frac{3}{2} p[\frac{i_x \Psi_d \Psi_q}{|\Psi_s|} + \frac{i_y \Psi_d^2}{|\Psi_s|} - \frac{i_x \Psi_d \Psi_q}{|\Psi_s|} + \frac{i_y \Psi_q^2}{|\Psi_s|}]$$

$$= \frac{3}{2} p|\Psi_s| i_y \tag{6}$$

Above equation indicates that the torque is directly proportional to the y –axis component of the stator current if the amplitude of the stator flux linkage is constant.

B. The generation of voltage vectors

The switches of the voltage source inverter are in 180° conducting mode means only three switching signal S_a, S_b and S_c are needed to uniquely determined the status of six switches. Assuming that the VSV is located in the a-axis of the a, b, c reference frame with phase a voltage Va applied alone, then the inverter output VSVs under different switching states can be expressed as[3]

$$v_s = \frac{2}{3} v_{dc}(S_a + aS_b + a^2 S_c) \tag{7}$$

C. Control of the stator flux linkage.

The stator flux linkage of a PMSM expressed in the stationary reference frame is,

$$\Psi_s = v_s - R_s \int i_s dt + \Psi_s|_{t=0} \tag{8}$$

Neglecting the stator resistance, the stator flux linkage can be directly defined by the integration of the voltage vector.

$$\Psi_s = v_s t + \Psi_s|_{t=0} \tag{9}$$

Equation (9) explains that the movement of the end of the stator flux linkage has the same direction with the given voltage vector and therefore, it is possible to control the amplitude, moving direction and moving speed of the stator flux linkage

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by selecting proper voltage vector$\Psi_s|_{t=0}$is the initial stator flux linkage at the instant switching.

D. The control of the rotation of stator flux linkage.

The torque of a PMSM with DTC could be effectively controlled by adjusting the rotating speed of the stator flux linkage under the condition of keeping its amplitude invariant, while the amplitude and rotating speed of the stator flux linkage are both controlled by selecting the proper voltage vector.

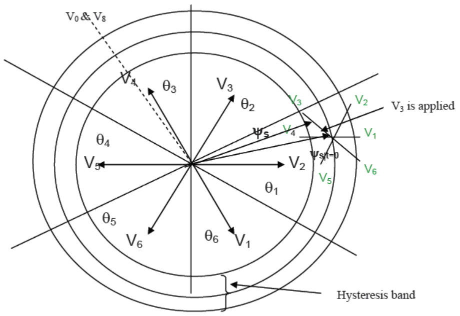

Fig.: 1 Voltage Space vector plane

The selection of VSV for the DTC of PMSM should be in such a way that when the torque is less than the reference, the VSV which could make the stator flux linkage vector rotate in its original direction should be selected. Due to the mechanical inertia of the rotor, the instantaneous velocity of the stator flux linkage could be much faster than that of the rotor flux linkage. An inverter-switching table can be arranged as shown in table I, where 'Φ' and 'τ' represent the outputs of flux linkage and electromagnetic torque hysteresis-loop controller, respectively; 'θ(1)-θ(6)' denote the section of the space vector plane where the present flux linkage vector is located; V is the VSV to be selected.[1]

Table 1

Φ	τ	θ					
		1	2	3	4	5	6
Φ=1	τ=1	V_2(110)	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_1(100)
	τ=0	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)	V_5(001)
Φ=0	τ=1	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_1(100)	V_2(110)
	τ=0	V_5(001)	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)

3. SIMULATION STUDY ON DTC FOR PMSM

The schematic diagram of DTC for PMSM is as shown in figure 2

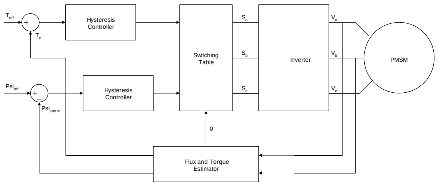

Fig.: 2 Schematic diagram of DTC for PMSM

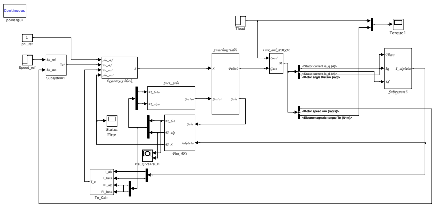

Fig.: 3 Simulink Diagram for DTC of PMSM

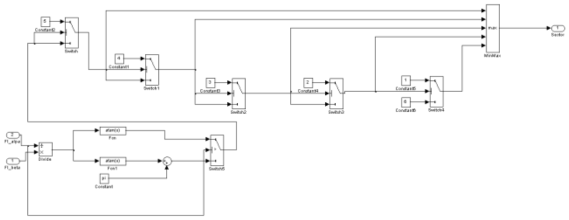

Fig.: 4 Angle calculation and sector judgment

The transformation of three-phase variables is into dq axes variables are done with following matrix [2]:

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{10}$$

where f represents the stator currents, voltages, and flux linkages.f_0 is zero for symmetrical stator windings. The three phase voltage are transformed into dq axes variables depending upon the values of switching signals S_a, S_b and S_c using

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{11}$$

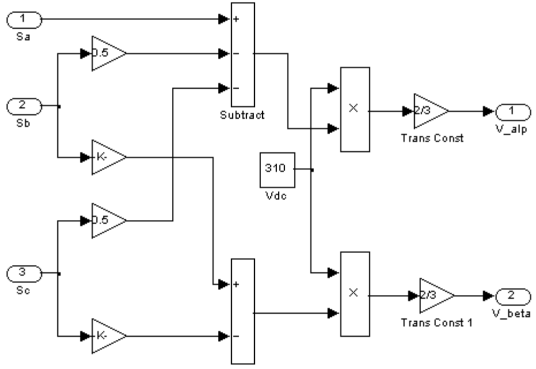

Fig.: 5 Generation of voltage signals

The reference torque is obtained from the output of the speed controller and is limited at a certain value, with respect to a given reference flux linkage, which guarantees the stator current not to exceed the limit value. The main advantage of DTC is that it is independent of motor parameters except stator resistance, which affects only the low-speed performance of the drive and can be compensated. The inductances and back EMF constant, which change with the saturation and temperature, respectively, are not used in the controller, and, therefore, there is no need to compensate for the saturation and back

EMF constant variation.

The system shown in figure 2 is simulated using Matlab software. A motor with pole saliency is considered for verification of the DTC concepts explained in earlier parts. A randomly varying is load torque is considered with an assumption that the rotor position at starting is zero. This assumption eliminates the need of encoder in the simulation.

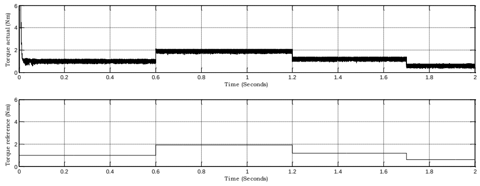

Fig.: 6 Torque response of PMSM with DTC drive

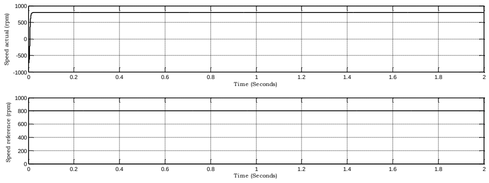

Fig.: 6 Speed response of PMSM with DTC drive

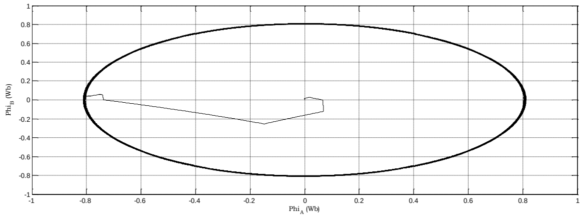

Fig.: 8 Stator flux trajectory

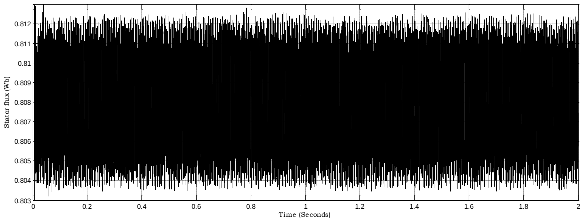

Fig.: 9 Stator flux

Table 2

Resistance R (Ω)	0.57
D-axis inductance [L_d](H)	$8.72 X 10^{-3}$
Q-axis inductance [L_q](H)	$22.8 X 10^{-3}$
Flux Induced by magnets (Wb)	0.808
Inertia(Jkgm^2)	$3.8 X 10^{-3}$
Friction factor	$0.1 X 10^{-3}$
Poles	4

4. CONCLUSION

The theoretical concepts related to DTC are explained. It has been mathematically proved that the increase of electromagnetic torque in a permanent magnet motor is proportional to the increase of the angle between the stator and rotor flux linkages, and, therefore, the fast torque response can be obtained by adjusting the rotating speed of the stator flux linkage as fast as possible. The implementation of DTC in the permanent magnet motor is discussed. The simulation results verify the proposed control and also show that the torque response under DTC is much faster than the one under current control.

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