SIMULATION OF DIRECT TORQUE CONTROLLED PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE

Selin Özçıra — e-mail: sozcira@yildiz.edu.tr
Nur Bekiroğlu — e-mail: nbekir@yildiz.edu.tr
Engin Ayçiçek — e-mail: eaycicek@yildiz.edu.tr
Yildiz Technical University, Department of Electrical Engineering, 34349 Besiktas, Istanbul, Turkey

Key words: Permanent magnet synchronous motor, direct torque control, space vector modulation

ABSTRACT

In this study, the structure and the control methods of permanent magnet synchronous motor (PMSM) are analysed and a simulation is realized using conventional Direct Torque Control (DTC) method. As a result of this analysis, it is observed that the increase of the electromagnetic torque is directly proportional to the increase of the angle between the stator and rotor magnetic flux linkages.

I. INTRODUCTION

Nowadays, as in every area of the technology, a development process has been proceeded in industrial driving systems. The improvement of the switching speeds of the switching equipment has enabled control techniques which have high switching frequency and feasibility of high efficiency driving systems.

Using complex control algorithms has become available with the development in microprocessor technology. The applications of vector control for induction and synchronous motors can be given an example of this. As a result of development of various algorithms for system modelling and control applications, induction and synchronous motors are being used in applications where DC motors were used.

However, induction motor's efficiency changes with slip value, it needs reactive current, and not able to produce the high torque / weight ratio which needed for high performance applications such as robotics, therefore different solutions are being studied, and different motor designs have been developed. One of these recently developed motors is the permanent magnet synchronous motor. In applications where high performance is demanded, some properties of the permanent magnet synchronous motor such as high torque, high power, high efficiency and low noise have made it more popular compared to other alternating current motors [1]. Especially because of the high power density, permanent magnet synchronous motor is applicable for areas such as robotics, automation and aeronautics technologies.

Since the excitation flux is supplied by the magnets and due to the magnet characteristics and location, permanent magnet synchronous motors have both of a synchronous machine and a direct current machine characteristics.

Unloaded conditions, velocity is directly proportional to voltage and inversely proportional to the flux and loaded conditions, it is directly proportional to the current and flux. Synchronous motors have three phase windings in their stators, just like the induction motors. However, the rotor structure is different. By using permanent magnets in stead of windings on the rotor, disadvantages of the brush and collector are eliminated. Also, since the excitation losses are eliminated, thermal limits are expanded and higher power values can be obtained from a machine of same volume. Using high energy permanent magnets such as Sm_2Co_{17} or Nd-Fe-B on the rotor, keeps the air gap flux density at higher values than of wounded machines and eliminates the copper losses of the rotor windings, thus provides the higher efficiency compared to the induction motors at identical power value. Also the motor dimensions are considerably reduced [2].

Permanent magnet synchronous motor is an AC motor that has windings in the stator slots. The flux generated by stator currents is almost sinusodial. Therefore, the same control methods used for the induction motors can also be used for the permanent magnet synchronous motors [3]. These controls are; V/f control, field oriented control, and direct torque control. The choice of direct torque control from these methods gives advantages such as; faster torque control, high torque at low level speed and high speed sensitivity.

II. DIRECT TORQUE CONTROL (DTC) OF THE PERMANENT MAGNET SYNCHRONOUS MOTOR

The torque of the permanent magnet synchronous motor is controlled by inspecting the armature current since electromagnetic torque is proportional to the armature current. For high dynamic performance, the current control is applied on rotor flux (dq) reference system that is rotated at synchronous speed. In this system, if the change of the back electromotor force (emf) and the inductance are sinusoidal, armature circuit inductance and magnet magnetic flux are constant. The main principle of DTC is to select the appropriate voltage vectors according to the stator magnetic flux, difference between the reference and real torque. The current control circuit that is constituted with the pulse width modulation (PWM) comparator circuit is not used in DTC. Therefore, if the DTC method is compared to PWM current control, it yields advantages such as; less parameter dependence and fast torque response. If the initial position of the rotor is known, it is possible to work with DTC without sensors [4].

III. MOTOR EQUATIONS IN STATOR FLUX REFERENCE SYSTEM

Stator magnetic flux vector ψ_s and rotor magnetic flux vector ψ_M, can be represented on rotor flux (dq), stator flux (xy) reference system as shown in Figure 1.
The angle between the stator and rotor magnetic fluxes δ, is the load angle. δ is constant for a constant load torque. In that case both the stator and the rotor fluxes rotate at constant speed. However under different loads δ varies. Either the stator current rotation speed or the variation of δ is controlled in order to control the increase of the torque.

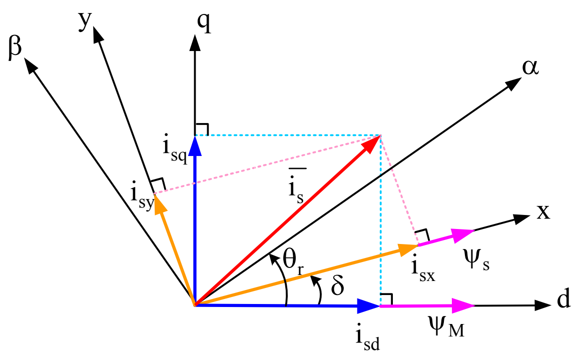

Figure 1. Stator and rotor magnetic fluxes in different reference systems

$$\psi_{sd} = L_{sd} i_{sd} + \psi_M \tag{1}$$

$$\psi_{sq} = L_{sq} i_{sq} \tag{2}$$

$$u_{sd} = R_s i_{sd} + \frac{d}{dt}\psi_{sd} - \omega_r \psi_{sq} \tag{3}$$

$$u_{sq} = R_s i_{sq} + \frac{d}{dt}\psi_{sq} + \omega_r \psi_{sd} \tag{4}$$

$$T_e = \frac{3}{2} p \left(\psi_{sd} i_{sq} - \psi_{sq} i_{sd} \right) \tag{5}$$

$$T_e = \frac{3}{2} p \left[\psi_M i_{sq} - \left(L_{sq} - L_{sd} \right) i_{sd} i_{sq} \right] \tag{6}$$

is obtained [5]. The symbols of parameters are as follows;

ψ_{sd} d axis stator magnetic flux,
ψ_{sq} q axis stator magnetic flux,
ψ_M rotor magnetic flux,
L_{sd} d axis stator leakage inductance,
L_{sq} q axis stator leakage inductance,
R_s stator winding resistance,
T_e electromagnetic torque,
p double pole number,

Using the transformation in equation (7) and Figure 1, the expressions (8) are obtained, using (8), equation (6), can be transformed into equation (9)

$$\begin{bmatrix} F_d \\ F_q \end{bmatrix} = \begin{bmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} F_x \\ F_y \end{bmatrix} \tag{7}$$

Here F represents the voltage, current and magnetic flux. Using Figure 1;

$$\sin\delta = \frac{\psi_{sq}}{|\psi_s|} \qquad \cos\delta = \frac{\psi_{sd}}{|\psi_s|} \tag{8}$$

is obtained. The expression $|\psi_s|$; represents the stator magnetic flux amplitude. When the necessary terms are placed using Figure 1, the following equation is obtained.

$$T_e = \frac{3}{2} p \left[\psi_{sd} \left(i_{sx} \sin\delta + i_{sy} \cos\delta \right) - \psi_{sq} \left(i_{sx} \cos\delta - i_{sy} \sin\delta \right) \right]$$

$$= \frac{3}{2} p \left[i_{sx} \frac{\psi_{sd}\psi_{sq}}{|\psi_s|} + i_{sy} \frac{\psi_{sd}^2}{|\psi_s|} - i_{sx} \frac{\psi_{sd}\psi_{sq}}{|\psi_s|} + i_{sy} \frac{\psi_{sq}^2}{|\psi_s|} \right]$$

$$T_e = \frac{3}{2} p |\psi_s| i_{sy} \tag{9}$$

It is clear that electromagnetic torque is directly proportional to the y-axis component of the stator current [6]. Controlling directly y-axis component of the stator current provides appropriate selection of the voltage switching vectors. Depending on less parameter is the main advantage of stator current control. It is possible to say that in a practical application the estimation technique shown in equation (6) requires saturation-dependent inductances. Therefore in equation (9) direct torque control over the stator current control is more convenient.

IV. STATOR MAGNETIC FLUX CONTROL

Torque can be controlled by keeping the stator magnetic flux constant and increasing the rotation speed. Stator magnetic flux and speed control is realized using the correct stator voltage vectors.

VOLTAGE SPACE VECTOR GENERATION

The main principle of DTC is determination of correct voltage vectors using the appropriate switching table. The determination process is based on the torque and stator magnetic flux hysteresis control. Stator magnetic flux can can be calculated using equation (10) [7].

$$\overline{\psi}_s = \int_{t}^{t+\Delta t} \left(\overline{u}_s - R_s \overline{i}_s\right) dt \qquad (10)$$

If the stator resistance is neglected in Equation (10), stator magnetic flux can be expressed directly as the integral of the voltage space vector.

$$\overline{\psi}_s = \int_{t}^{t+\Delta t} \overline{u}_s dt \qquad (11)$$

Equation (11) shows that the stator magnetic flux and the voltage space vector have the same direction. Therefore, stator magnetic flux amplitude and direction control is feasible by using the correct voltage space vector. The voltage vectors are determined in order to control the stator magnetic flux amplitude. Voltage vector plane is divided into six sections as shown in Figure 2. Two adjacent voltage vectors that yield the lowest switching frequency are selected in order to increase or decrease the amplitude of ψ_s.

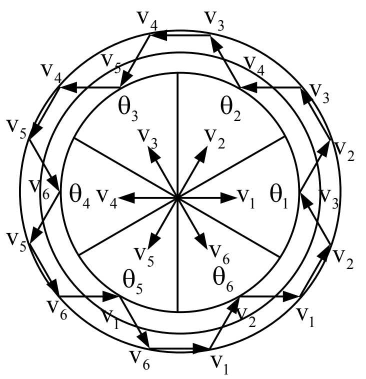

Figure 2. Vectors for space vector modulation

Here, when the stator magnetic flux is moved clockwise in section 1, voltage space vector v_2 is selected in order to increase the stator magnetic flux amplitude and voltage space vector v_3 is selected in order to decrease the amplitude.

When the stator magnetic flux moves clockwise, if still in section 1, v_6 is used to increase the amplitude and v_5 is used to decrease the amplitude. The torque of the permanent magnet synchronous motor can be controlled using DTC by means of controlling the stator magnetic flux rotation speed in cases where the stator magnetic flux amplitude is kept constant. However, since the magnets on the rotor are continuously rotating, stator magnetic flux does not change when v_0 and v_8 zero vectors are used. Therefore, zero vectors are not used in DTC for permanent magnet synchronous motors [8].

V. MODEL VERIFICATION

Here the MATLAB/Simulink model of the permanent magnet synchronous motor is developed according to the dq model. In the simulation, the stator magnetic flux amplitude value is assumed to be the same as the value of the permanent magnet flux. Meaning that flux reference is applied as 0.533Wb. The inverter dc bus voltage is 164.4V. Also at t=0.03s, a differential step from 2Nm to -2Nm and at t=0.09s from -2Nm to 2Nm is applied to the referans torque value. Motor parameters are;

p=2, $R_s = 5.8\Omega$, $\psi_M = 0.533\text{Wb}$, $L_{sd} = 44.8\text{mH}$, $L_{sq} = 102.7\text{mH}$, $J = 0.000329\text{kgm}^2$, $B_m = 0.0003882$

Figure 3 shows the simulink diagram of the direct torque control for permanent magnet synchronous motor.

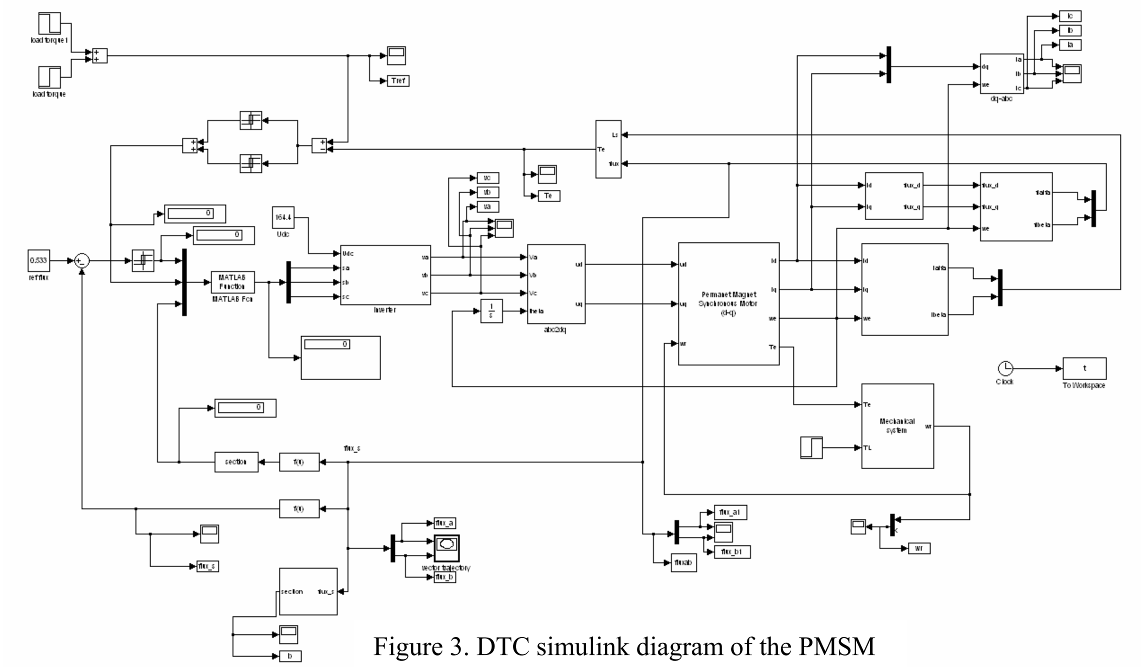

Figure 3. DTC simulink diagram of the PMSM

VI. SIMULATION RESULTS

The system dynamic responses are shown below with a sampling time 100µs.

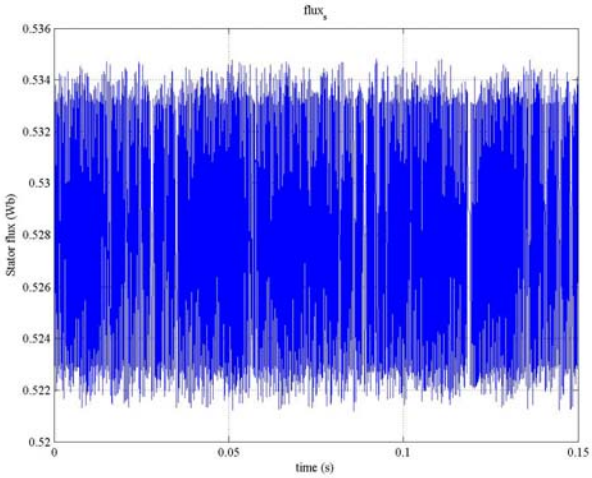

Figure 4. Stator magnetic flux simulation response

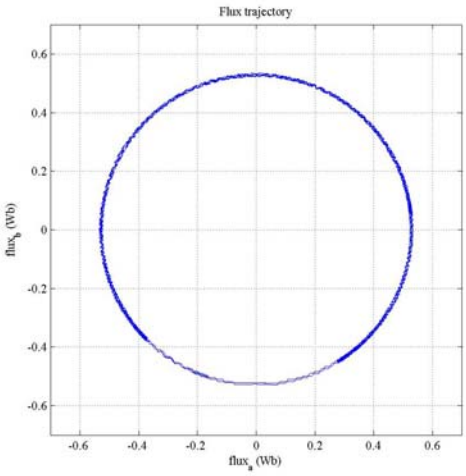

Figure 5. Stator magnetic flux vector trajectory simulation

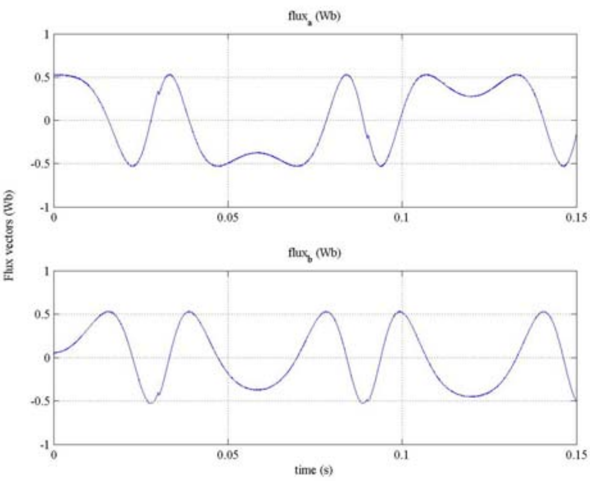

Figure 6. Stator magnetic flux vector simulation response

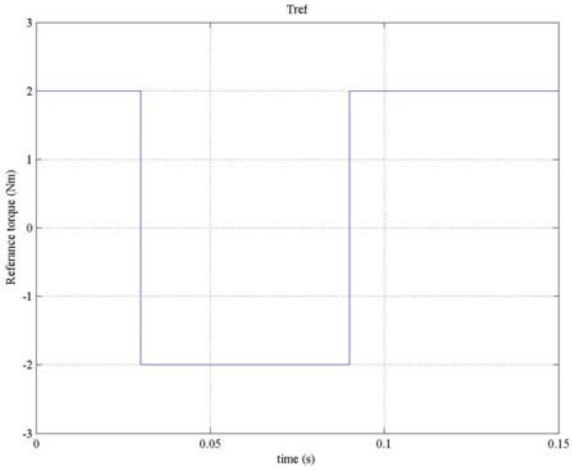

Figure 7. Reference torque simulation response

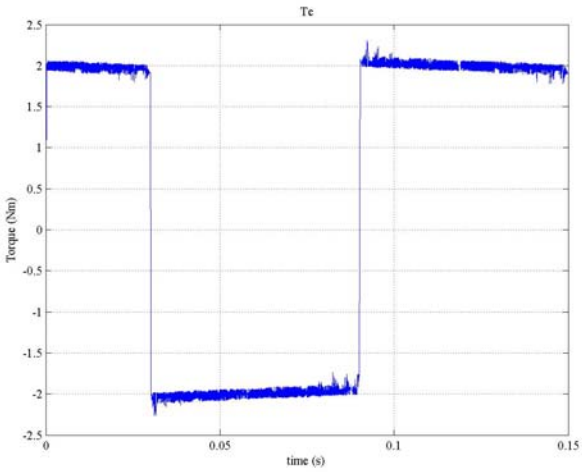

Figure 8. Actual torque simulation response

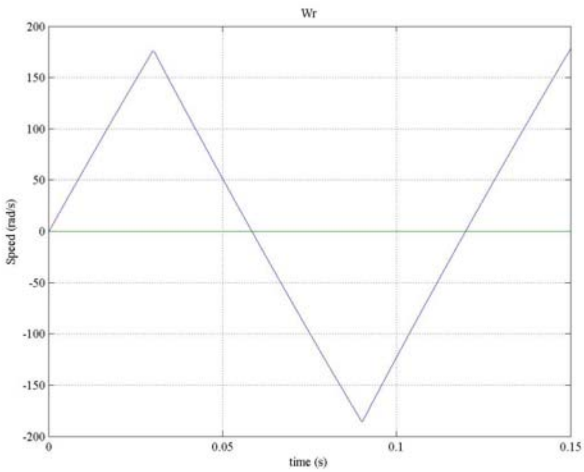

Figure 9. Speed simulation response

VII. CONCLUSION

Motor criteria such as durability, high performance, high power factor, easy and cheap control, low maintenance demands have led to a new type of motor excitated by permanent magnets. In this study, control methods of permanent magnet synchronous motor are analysed and by means of space vector theory, direct torque control DTC method is used to control the motor.

DTC is intended for an efficient control of the torque and flux without changing the motor parameters and load. Also the flux and torque can be directly controlled with the inverter voltage vector in DTC. Two independent hysteresis controllers are used in order to satisfy the limits of the flux and torque. These are the stator flux and torque controllers.

In the performed simulation, certain stator flux and torque references are compared to the values calculated in the driver and errors are send to the hysteresis comparators. The outputs of the flux and torque comparators are used in order to determine the appropriate voltage vector and stator flux space vector. Vector locations are shown in Figure 5.

In this study, DTC process of the permanent magnet synchronous motor is explained and a simulation is constituted. It is concluded that DTC can be applied for the permanent magnet synchronous motor and is reliable in a wide speed range. Especially in applications where high dynamic performance is demanded DTC has a great advantage over other control methods due to its property of fast torque response. In order to increase the performance, control period should be selected as short as possible. When the sampling interval is selected smaller, it is possible to keep the bandwidth smaller and to control the stator magnetic flux more accurately. Also it is important for the sensitivity to keep the DC voltage in certain limits. As a improvement approach, a LP filter can be added to the simulation in order to eliminate the harmonics.

REFERENCES

1. Laurent, J., Jabbar, M. A.,Qinghua, L., “Optimization of the Constant Power Speed Range of a Saturated Permanent-Magnet Synchronous Motor”, IEEE Transactions on Ind. App., Vol.42, No.4, pp. 1024-1030, 2006.
2. Texas Instruments, “Digital Signal Processing Solution for Permanent Magnet Synchronous Motor”, Application Note Literature Number: BPRA044, pp. 11-13,1997.
3. Bizot, C., Brottes, J., Lungeanu, M., Poulsen, B., Séra, D., Sørensen, M. B., “Sensorless Control for PMSM”, Power Electronics and Drives, Institute of Energy Technology, Aalborg University, Denmark, 2003.
4. Zhong, L., Rahman, M. F., Hu, W. Y., Lim, K. W., “Analysis of Direct Torque Control in Permanet Magnet Synchronous Motor Drives”, IEEE Transactions on Power Electronics, pp. 528-536, 1997.
5. Tang, P., Yang, G., Luo, M., Li, T., “A Current Control Scheme with Tracking Mode for PMSM System”, Systems and Control in Aerospace and Astronautics 1st International Symposium, pp. 872-876, 2006
6. Luukko, J., Pyrhönen, J., “Selection of the Flux Linkage Reference in a Direct Torque Controlled Permanent Magnet Synchronous Motor Drive”, IEEE, in Proc. AMC ’98-COIMBRA, pp. 198-203, 1998.
7. Rahman, M. F., Zhong, L., Haque, E., “ Selection of Voltage Switching Tables for DTC Controlled Interior Permanent Magnet Motor”, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, NSW 2052 Australia, 1999.
8. Sun, D., Weizhong, F., Yikang, H., “Study on the Direct Torque Control of Permanent Magnet Synchronous Motor Drives”, Electrical Machines and Systems, ICEMS 2001. Proceedings of the Fifth International Conference, pp. 571-574, 2001.
9. “SIMULINK Dynamic System Simulation for MATLAB Modeling, Simulation, Implementation”, The MathWorks, Inc. Natick, Massachusetts, USA, 1998.