

Comparative study of PMSM and IM Based on Direct Torque Control Method

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Abstract-The direct torque control theory has achieved great success in the control of induction motor and Permanent Magnet Synchronous Motor. Many attempts have been made to implement the idea of DTC of induction motor to PMSM since 1990's. The DTC is implemented by selecting the proper voltage vector according to the switching status of inverter which was determined by the error signals of reference flux linkage and torque with their measured real value acquired by calculating in the stationary reference frame by means of simply detecting the motor voltage or currents. Aiming at the DTC in PMSM Drives, this project explained the theoretical basis of the direct torque control (DTC) for PMSM firstly. Then explained the difference between the application of DTC to PMSM and to IM. Finally the Mat lab/Simulink models were developed to examine the DTC for PMSM and IM. The simulation results is presented and explained in detail.

1. INTRODUCTION: Modern electrical driver systems consist of power electronics transformers, analog/digital controllers and sensors or observers. DC, asynchronous and synchronous motors are frequently used motor types with these driver systems. New kinds of motors are developed like linear motors, step motors, switching reluctance motors, and permanent magnet synchronous motors. Permanent magnet synchronous motors are

used where in general high demands are made with regard to speed stability and the synchronous operation of several interconnected motors. They are suitable for applications where load independent speeds or synchronous operation are required under strict observance of defined speed relations within a large frequency range. Most of the industrial motor applications use AC induction motors. The reasons for this include high robustness, reliability, low price and high efficiency. Industries have many applications, where variable operating speed is a prime requirement. In many applications, operating the plant at a reduced speed when full output is not needed produces a further important benefit: energy savings and reduced cost. Plant wear and hence, maintenance requirements, are also minimized by operation at reduced speed.

Permanent magnet synchronous motors (PMSM) are widely used in low and mid power applications such as computer peripheral equipments, robotics, adjustable speed drives and electric vehicles. The growth in the market of PMSM motor drives has demanded the need of simulation tool capable of handling motor drive simulations. Simulation tools have the capabilities of performing dynamic simulations of motor drives in a visual environment so as to facilitate the development of new systems. In this work, the simulation of a direct torque control of PMSM is developed using Simulink. The Direct Torque Control is one of the high performance control strategies for AC machine. The DTC scheme has been realized successfully in the

Induction Motor drives. The aim of the paper is to study the implementation of the Direct Torque Control (DTC) in Permanent Magnet Synchronous Motor (PMSM) and Induction Motor (IM).

2. PERMANENT MAGNET SYNCHRONOUS MOTOR

The Permanent Magnet Synchronous Motor (PMSM) has numerous advantages over other machines that are conventionally used for ac servo drives. The stator current of the induction motor (IM) contains magnetizing as well as torque-producing components. The use of the permanent magnet in the rotor of the PMSM makes it unnecessary to supply magnetizing current through the stator for constant air-gap flux; the stator current need only be torque producing. Hence for the same output, the PMSM will operate at a higher power factor (because of the absent of magnetizing current) and will be more efficient than Induction Motor. The development of the PMSM was to remove the foregoing disadvantages of the Synchronous Motor by replacing its field coil, DC power supply and slip rings with a permanent magnet.

2.1 MOTOR EQUATIONS

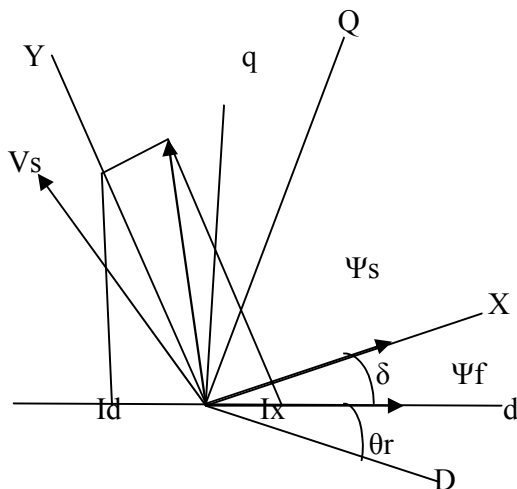


Fig.1 Rotor and stator and rotor flux linkages in different terms

The stator flux linkage vector ψ_s and rotor flux linkage ψ_f of PMSM can be drawn in the rotor flux (dq), stator flux (xy), and stationary (DQ) frames as shown in figure 1.

The well-known voltage equations in the rotor reference frame are as follows:

$$v_d = R_d i_d + \frac{d}{dt} \psi_d - \omega_r \psi_q \quad (1)$$

$$v_q = R_q i_q + \frac{d}{dt} \psi_q + \omega_r \psi_d \quad (2)$$

Where R_d and R_q are the quadrature and direct-axis winding resistances which are equal and be referred to as R_s is the stator resistance.

The developed torque motor is being given by

$$T_e = \frac{3}{2} P (\psi_d i_q - \psi_q i_d) \quad (3)$$

Which upon substitution of the flux linkages in terms of the inductances and current yields

$$T_e = \frac{3}{2} P (\psi_f i_q + (L_d - L_q) i_d i_q) \quad (4)$$

the mechanical Torque equation is

$$T_e = T_L + B\omega_m + J \frac{d\omega_m}{dt} \quad (5)$$

3. INDUCTION MOTOR

The steady-state model and equivalent circuit are useful for studying the performance of machine in steady state. This implies that all electrical transients are neglected during load changes and stator frequency variations. Such variations arise in applications involving variable-speed drives. The dynamic model considers the instantaneous effects of varying voltages/currents, stator frequency and torque disturbances. The dynamic model of induction motor is derived by using a two-phase motor in direct and quadrature axes. This approach is desirable because of the conceptual simplicity

obtained with the two sets of the windings, one on the stator and the other on the rotor.

3.1 MOTOR EQUATIONS

The dynamic behavior of an induction machine is described by the following equations written in terms of space vectors in a stator reference frame

$$V_s = R_s I_s + \frac{d\varphi_s}{dt} \quad (6)$$

$$0 = R_r I_r + \frac{d\varphi_r}{dt} - j\omega_m \varphi_r \quad (7)$$

$$\varphi_s = L_s I_s + M I_r \quad (8)$$

$$\varphi_r = L_r I_r + M I_s \quad (9)$$

Where R_s and R_r are represented the stator and rotor resistances. L_s and L_r represent self and mutual inductances. ω_m Represents rotor angular speed expressed in electrical radians. The electromagnetic torque is expressed in terms of stator and rotor fluxes as

$$T = P \frac{M}{\sigma L_s L_r} (\varphi_s \cdot j\varphi_r) \quad (10)$$

Where P is the pole pair number.

$$\sigma = 1 - \frac{M^2}{L_s L_r} \quad (11)$$

4. DIRECT TORQUE CONTROL PRINCIPLE

In a DTC drive, flux linkage and electromagnetic torque are controlled directly independently by the selection of optimum inverter switching modes. The selection is made to restrict the flux linkages and electromagnetic torque errors within the respective flux and torque hysteresis bands, to obtain fast torque response, low inverter

switching frequency and low harmonic losses. The required optimal switching vectors can be selected by using so-called optimum switching-voltage vector look-up table. This can be obtained by simple physical considerations involving the position of the stator-flux linkage space vector, the available switching vectors, and the required torque flux linkage.

The speed control loop and the flux program as a function of speed are shown as usual and will not be discussed. The command stator flux and torque magnitudes are compared with the respective estimated values and the errors are processed through hysteresis-band controllers, as shown. The flux loop controller has two levels of digital output according to the following relations:

$$H_\psi = 1 \quad \text{for} \quad E_\psi > +HB_\psi \quad (12)$$

$$H_\psi = -1 \quad \text{for} \quad E_\psi < -HB_\psi \quad (13)$$

The torque control loop has three levels of digital output, which have the following relations:

$$H_{T_e} = 1 \quad \text{for} \quad E_{T_e} > +HB_{T_e} \quad (14)$$

$$H_{T_e} = -1 \quad \text{for} \quad E_{T_e} < -HB_{T_e} \quad (15)$$

$$H_{T_e} = 0 \quad \text{for} \quad -HB_{T_e} < E_{T_e} < +HB_{T_e} \quad (16)$$

The feedback flux and torque are calculated from the machine terminal voltages and currents. The signal computation block also calculates the sector number in which the flux vector lies.

The voltage vector table block in Figure 2 receives the input signals H_ψ , H_{T_e} , and $S(k)$ and generates the appropriate control voltage vector (switching states) for the inverter by lookup table, which is shown in table 1 (the vector sign is deleted).

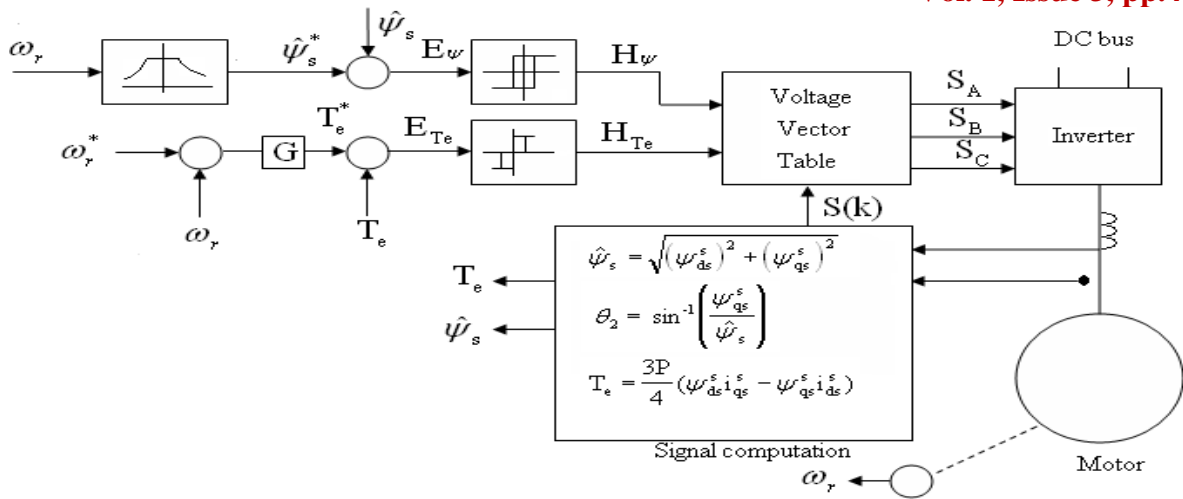


Figure 2. Direct Torque and Flux control block diagram

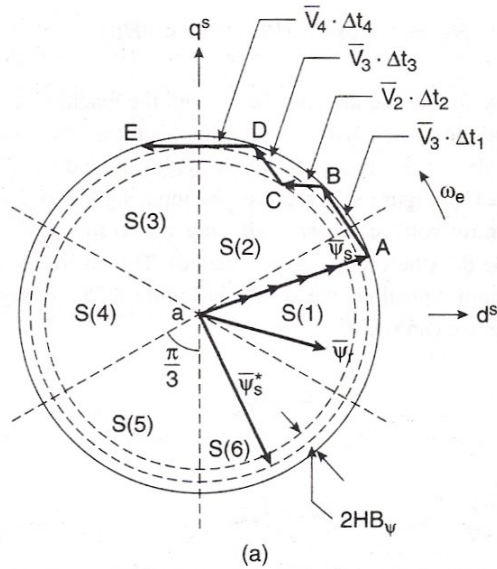


Figure.3 Trajectory of stator flux vector in DTC control

$$\bar{V}_s = \frac{d}{dt}(\bar{\psi}_s) \quad (17)$$

$$\Delta \bar{\psi}_s = \bar{V}_s \cdot \Delta t \quad (18)$$

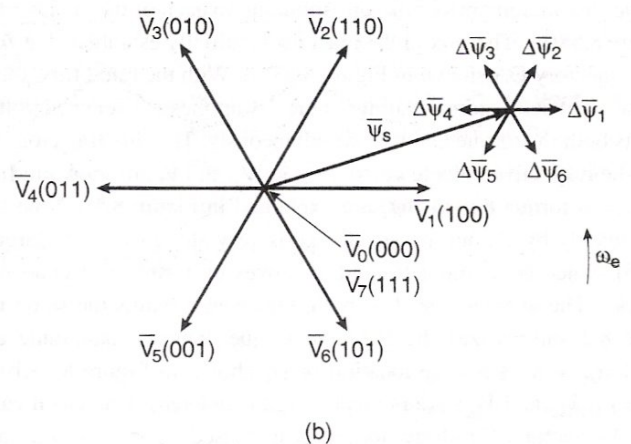


Figure.4 Inverter voltage vectors

The inverter voltage vector (six active and two zero states) and a typical $\bar{\psi}_s$ are shown in Figure 3(a). Neglecting the stator resistance of the machine, we can write

Which means that $\bar{\psi}_s$ can be changed incrementally by applying stator voltage \bar{V}_s for time increment Δt . The flux increment vector corresponding to each of six inverter voltage vectors is shown in Figure 4(b). The flux in machine is initially established to at zero

frequency (dc) along the trajectory OA shown in Figure 3. With the rated flux the command torque is applied and the $\bar{\psi}_s^*$ vector starts rotating. Table 1 applies the selected voltage vector, which essentially affects both the torque and flux simultaneously. The flux trajectory segments AB, BC, CD and DE by the respective voltage vectors $\bar{V}_3, \bar{V}_4, \bar{V}_3,$ and \bar{V}_4 are shown in Figure 3(a). The total and incremental torque due to $\Delta\bar{\psi}_s$ are explained in figure 1. Note that the stator flux vector changes quickly by, but the $\bar{\psi}_r$ change is very sluggish due to large time constant T_r . Since $\bar{\psi}_r$ is more filtered, it moves uniformly at frequency ω_e , whereas $\bar{\psi}_s$ movement is jerky. The average speed of both, however, remains the same in the steady-state condition. Table 1 summarizes the flux and torque change (magnitude and direction) for applying the voltage vectors for the location of $\bar{\psi}_s$ shown in Figure 4. The flux can be increased by the $\bar{V}_1, \bar{V}_2,$ and \bar{V}_6 vectors (vector sign is deleted), whereas it can be decreased by the $\bar{V}_3, \bar{V}_4,$ and \bar{V}_5 vectors.

H_ψ	H_{Te}	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1	V2	V3	V4	V5	V6	V1
	0	V0	V7	V0	V7	V0	V7
	-1	V6	V1	V2	V3	V4	V5
-1	1	V3	V4	V5	V6	V7	V2
	0	V7	V0	V7	V0	V7	V0
	-1	V5	V6	V1	V2	V3	V4

Table 1.Switching Table of Inverter Voltage Vectors

Similarly, torque is increased by the $\bar{V}_2, \bar{V}_3,$ and \bar{V}_4 Vectors, but decreased by the $\bar{V}_1, \bar{V}_5,$ and \bar{V}_6 vectors. The zero vectors (V_0 or V_7) short-circuit the machine terminals and keep the flux and torque unaltered. Due to finite resistance (R_s) drop, the torque and flux will slightly decrease during the short-circuit condition.

Voltage Vector	V1	V2	V3	V4	V5	V6	V0 Or V7
Ψ_s	↑	↑	↓	↓	↓	↑	0
T_e	↓	↑	↑	↑	↓	↓	↓

Table 2.Flux and Torque Variations due to applied voltage vectors

Consider for example, an operation in sector S (2) as shown in Figure 3(a), where at point B, the flux is too high and the torque is too low; that is, $H_\psi = -1$ and $H_{Te} = +1$. From table 1, voltage V_4 is applied to the inverter, which will generate the trajectory BC. At point C, $H_\psi = +1$ and $H_{Te} = +1$ and this will generate the V_3 vector from the table. The drive can easily operate in the four quadrants, and speed loop and field-weakening control can be added, if desired. The torque response of the drive is claimed to be comparable with that of a vector-controlled drive. Consider for example, an operation in sector S (2) as shown in Figure 3(a), where at point B, the flux is too high and the torque is too low; that is, $H_\psi = -1$ and $H_{Te} = +1$. From table 1, voltage V_4 is applied to the inverter, which will generate the trajectory BC. At point C, $H_\psi = +1$ and $H_{Te} = +1$ and this will generate the V_3 vector from the table. The drive can easily operate in the four

quadrants, and speed loop and field-weakening control can be added, if desired. The torque response of the drive is claimed to be comparable with that of a vector-controlled drive.

5. IMPLEMENTATION OF DTC FOR PMSM

Simulink® model of low voltage - high power Surface mounted PMSM is developed according to the dq model. The inverter dc bus voltage is 510V. Also $t=0$ between 0.4s 13rad/s and at $t=0.4s$ -13rad/s differential step is

applied to the reference speed. According to observe adaptation of the actual speed at $t=0.2s$ 60 Nm is applied to load torque value. Motor parameters are;

$P_n = 18Kw$ $I_n = 50A$, $R_s = 0.43\Omega$, $L_d = 25mH$, $L_q = 25mH$ $\psi_M = 1.58Wb$, $J = 2.16kgm^2$, $B_m = 0.005538$, $p=10$ Fig. 5 shows the speed control Simulink® diagram of the direct torque control for permanent magnet synchronous motor.

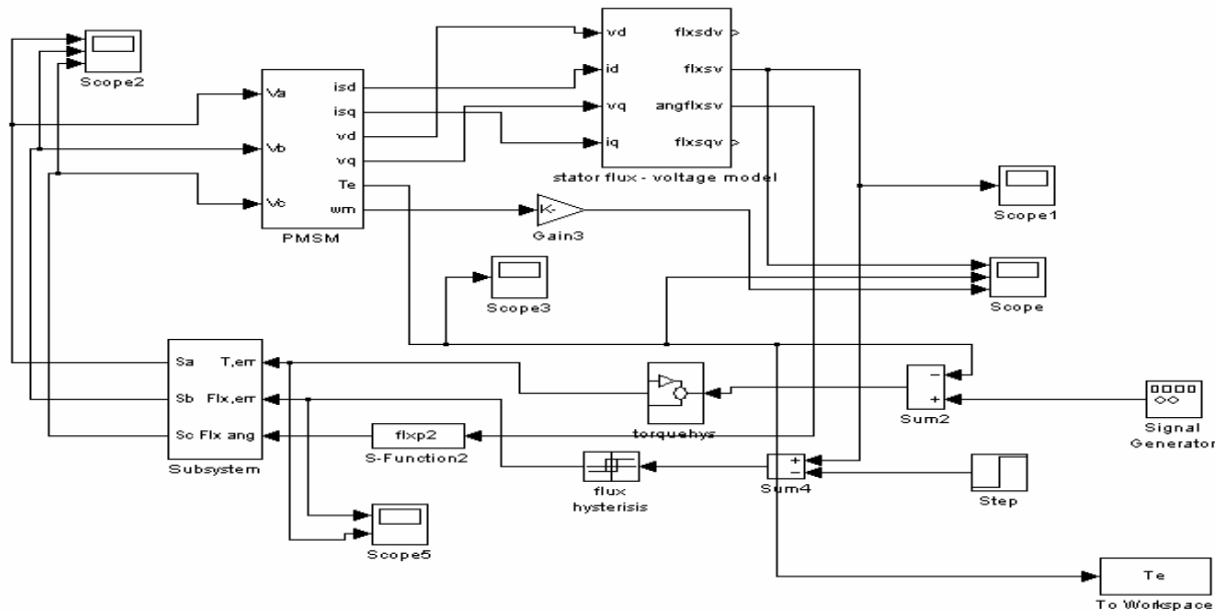


Figure.5 Simulink model of PMSM based on Direct Torque Control Method

5. IMPLEMENTATION OF DTC FOR IM

Simulink® model of low voltage - high power Surface mounted INDUCTION MOTOR is developed according to the dq model.

Motor parameters are;

Stator Resistance 6.03 ohm
 Rotor resistance 6.085 ohm
 Stator inductance 489.3e-3 H
 Rotor Inductance 489.3e-3 H

Mutual Inductance 450.3e-3 H
 Number of Poles 4
 Moment of Inertia 0.00488 kg.m²
 Dc link voltage 2*190
 Reference Speed 157 rad/sec.
 Proportional Constant 5.
 Integrator Constant 0.75.

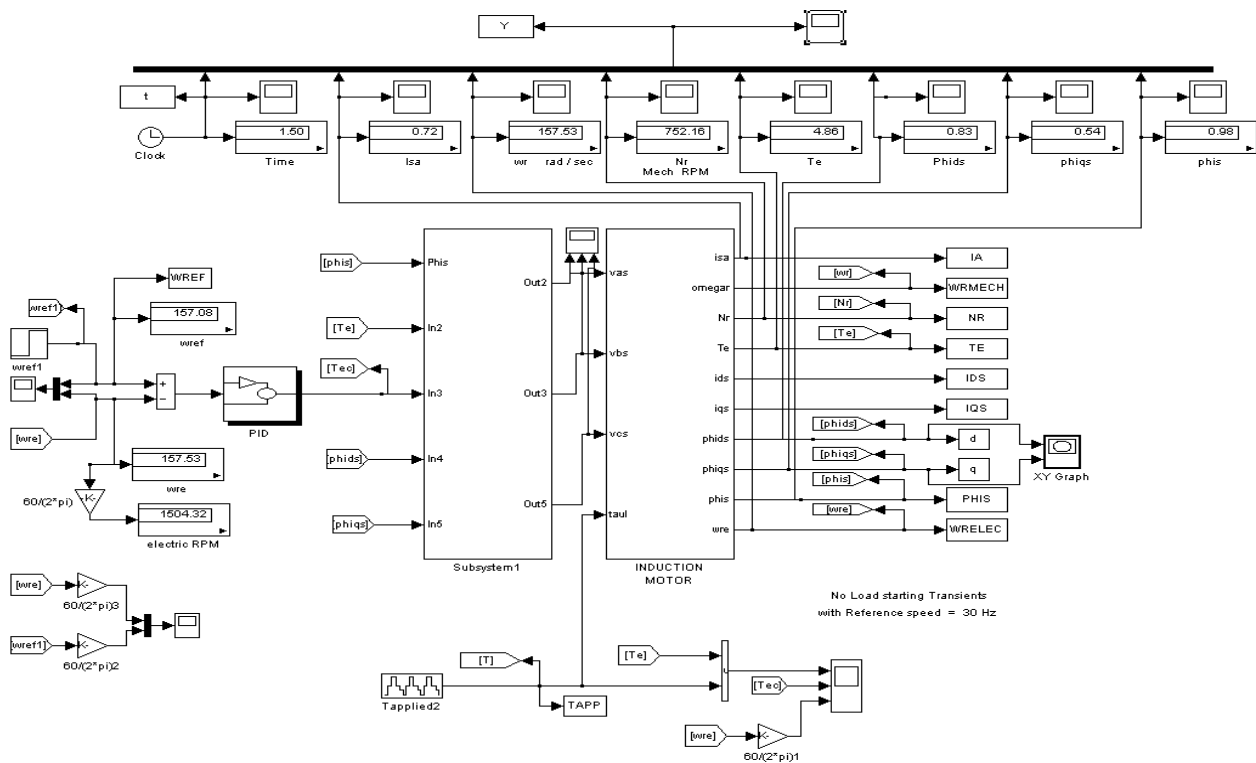
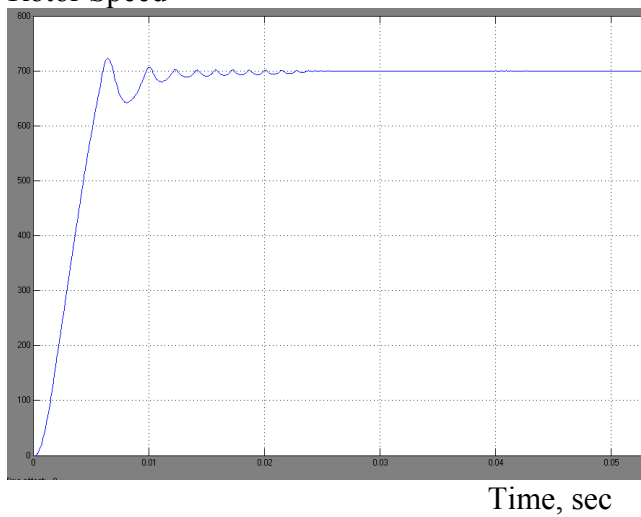


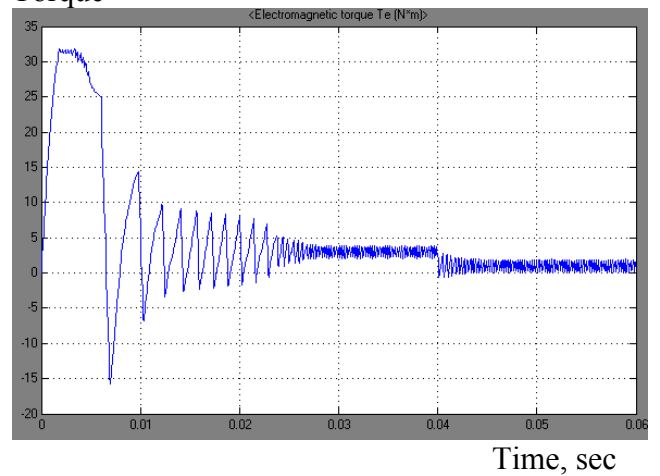
Figure.6 Simulink model of IM based on Direct Torque Control Method

7. SIMULATION RESULTS

7.1 Simulation result for DTC of PMSM Rotor Speed

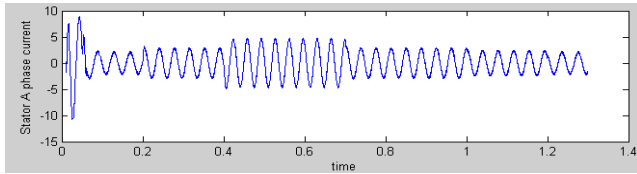


Torque

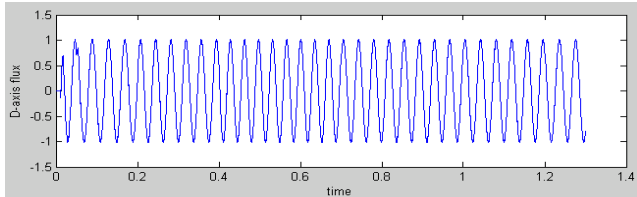


7.2 Simulation result for DTC of IM

WHEN LOAD IS APPLIED
Stator phase current

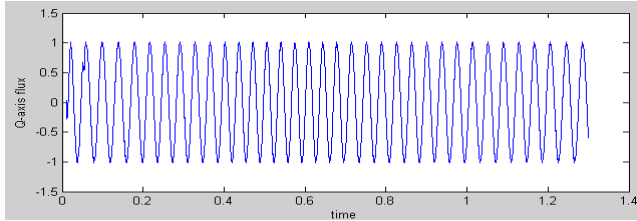


D axis flux



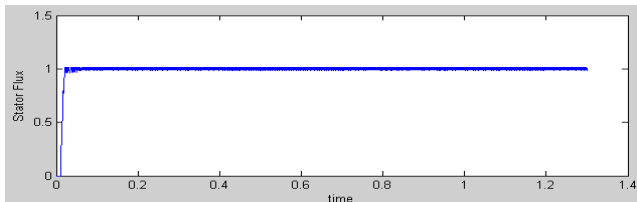
Time, sec

Q axis flux



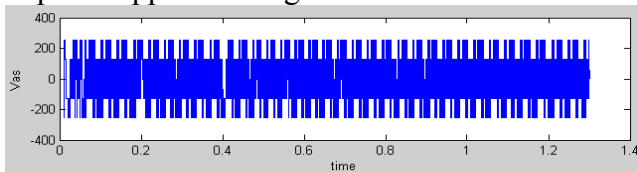
Time, sec

Stator flux



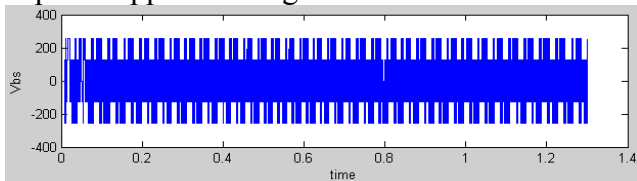
Time, sec

A phase applied voltage



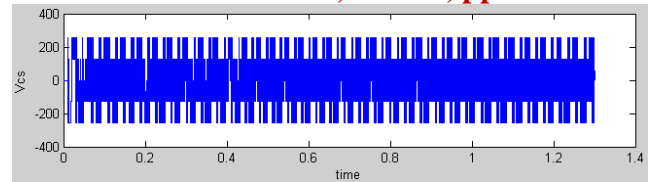
Time, sec

B phase applied voltage



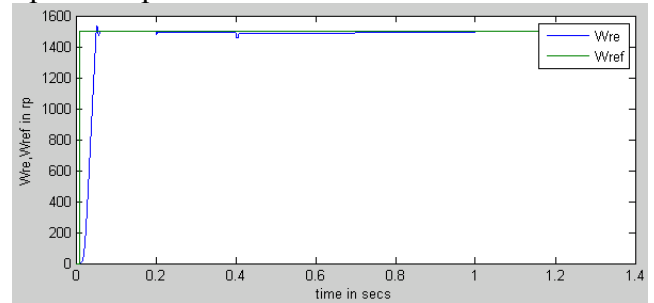
Time, sec

C phase applied voltage



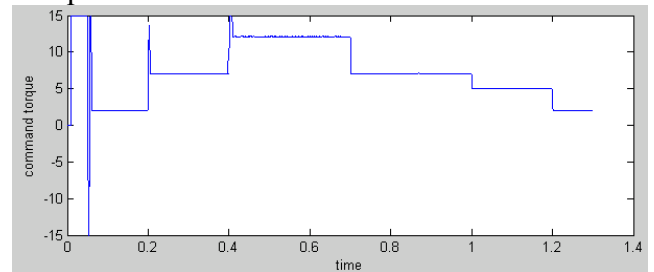
Time, sec

Speed in rpm



Time, sec

Torque



Time, sec

8. CONCLUSION

Since the introduction of DTC a lot of research has been done to improve the performance of DTC drives while maintaining the good properties such as low complexity, good dynamic response, high robustness. This thesis explained the mathematical equations related to the application of DTC in PMSM. The equations show that the change of torque can be controlled by keeping the amplitude of the stator flux linkage constant and increasing the rotating speed of the stator flux linkage as fast as possible. The amplitude and rotating speed of the stator flux linkage can be controlled by selecting the proper stator voltage vectors. The differences in the

DTC technique for PMSM and IM are presented. The simulink block of DTC in PMSM and IM are presented. The simulation results examined the implementation of the direct torque control in permanent magnet synchronous motor and compared its performance with induction motor. The torque and flux linkage reference are kept constant at the same level. A detailed Simulink model for DTC of PMSM and IM has being developed. Simulink has been chosen from several simulation tools because its flexibility. Mathematical models can be easily incorporated in the simulation and the present numerous toolboxes and support guides simplified the simulation of large system compared to other software. Simulink is capable of showing real time results with reduced simulation time and debugging. It is shown in the simulation results of DTC in PMSM and IM that the DTC implemented in PMSM having less level of torque and flux ripples and at the same time maintaining good torque response.

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