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Performance Evaluation of Interior Permanent Magnet Synchronous Motor using Direct Torque Control Strategy

Abstract

The direct torque control(DTC) is very much successful in controlling induction motor(IM).Since 1990's research is going on well for implementing DTC to IM. DTC include the selection of voltage vector with inverter switchings that are obtained by comparing flux and torque signals with their reference values there by motor voltages and currents can be generated. Paper describes the DTC which has been applied to Permanent Magnet Synchronous Motor(PMSM). Matlab/Simulink was used to implement the DTC to PMSM. Simulation outcomes are given and explained in brief.

Keywords: Permanent Magnet Synchronous Motor, Direct Torue Control,Torue and flux hystereis controllers

1. INTRODUCTION

With the increase of usage PMSM, it needs simulation tools which are used to control the drive in different conditions. PMSM has many applications than other AC drives [1]. Usage of bar magnet avoids the need of flux producing current that leads simplified analysis of this machine [2]. Because of this operating p.f of this machine is more when compared to other conventional drives[3].

In 1987 Depenbrock provided a control which is like proposed one. During later work by Takahasi and Ohmori the technique named the DTC . Initially in industry this method is applied by Tiitenen. Later more ofwork done on DTC implemented to to synchronous motor[4]. Recently also DTC improved in application to PMSM[5].

L.Zhong explained about this application. Rahman has given the excellent work performance in DTC of this PMSM. This sceheme has too many features than FOC

Rahman also provided work on detection of speed without any snsors that is by using angle of torque and flux[6]. Beside FOC this techniques has many improvements in torque ripple [7]. Matlab simulation of DTC is done to PMSM is this paper.

2. PERMANENT MAGNET SYNCHRONOUS MOTOR

Coil of field ,slip rings and direct current supplies are removed with usage of PMSM than conventional system with field winding system.[8]

Motor Equation

Vector of Flux in stator i s ψ_s and in rotor ψ_f of PMSM is shown in rotor flux of dq, flux in stator as coordinates, stationary (DQ) frames which are expressed in figure(1).

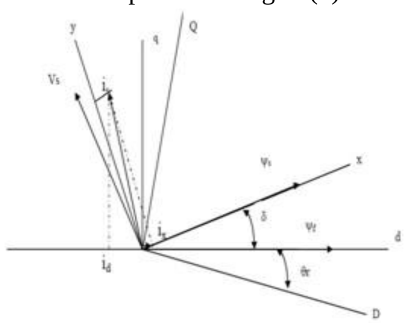

Figure.2.1: Flux's of stationary and rotational parts in various frames

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These frames will be considered as revolving with rotor speed when these are taken in rotor side frame. Load angle δ is the angular difference between both fluxes of stator and rotor with nullifying ohmic resistance in stationary winding. During steady state, δ will be steady equivalent to a load torque and fluxes of both parts runs at synchronous speed. But during load change operations δ changes and the stator ,rotor flux rotates with dissimilar speeds[9].
The well-known equations for voltages in reference frame of rotor in matrix form:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_q + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_d + \rho L_d \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \omega_r L_m i_f \\ \rho \psi_f \end{bmatrix} \quad (1)$$

Total torque is

$$T_e = T_L + B\omega_m + J \frac{d\omega_m}{dt} \quad (2)$$

speed of motor from equation(3) can be written as

$$\omega_m = \int((T_e - T_L - B\omega_m)/J)\, dt \quad (3)$$

Electrical speed quantity will be equal to P/2 times the speed in mechanical.

$$T_e = 1.5\, P\, [\, \psi_d (i_x \sin\delta + i_y \cos\delta) - \psi_q (i_x \cos\delta + i_y \sin\delta)\,] \quad (4)$$

In this way torque can be generated from d and q axis components.

Control Schemes of PMSM:

Scalar Control

In this technique magnitude and frequency of voltage will be controlled. It is easy controlling method. It comes under open loop control. Flux will be maintained as same value so that torque will also be same that too at maximum value at various speeds[10]

Vector Control

There is coupling action between torque and flux in previous control and this causes stability problem.
Vector control is used to control value of flux's of stator and rotor along with angle between flux's.
Field Oriented Control(FOC)

FOC generally maintains 90 degrees angular difference between the two fields. It can be easily applied to machines. It generates a smaller amount ripple with little complexity in system and not that much robust like DTC.

Direct Torque Control

DTC was developed in 1980's century for torque and flux control of IM. It is used in in 1990's for PMSM. This technique became very popular method due to its easy and simple applicability.

The operation of DTC is to directly s e l e c t vectors of voltages with respect to the variation between reference and measured values of flux, torque. Hysteresis comparator is used to compare the errors of both flux and torque and according this comparison a vector of voltage will be generated. Main feature of DTC is less in complex. With out any pulse width modulation vector of voltage will be chosen during sampling time. Simplifications and analysis were done in reference frame of stator instead in reference frame of rotor. Rotor location is identified in running in a synchronous motor

In the digital implementation this technique takes low power. Although it is giving better transient response but in final state ripple content may exist in torque due to lack of smoothness in current. This takes less computational time even at large frequency due to its simplicity

3. PROPOSED METHODOLOGY:

Direct Torque Control:

Block diagram of DTC is given in figure 3.1, where the estimator is used to measure flux and torque.

Torque and flux are controlled with use of these hysteresis controllers. Voltage vector will be selected and applied to motor with the switching of inverter leg due to output generated from hysteresis controllers [11].

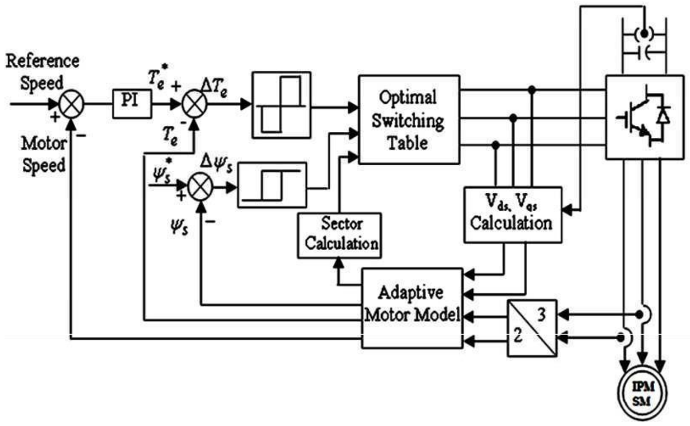

Figure 3.1: **Fundamental DTC diagram of PMSM**

Flux and Torque Estimator

By integrating the error generated d-axis input voltage and the drop due to d-axis current ,the d-axis component of flux can be generated as

$\Psi_d = \int (\upsilon_d - R_s i_d)\, dt$ (5)

By using same, the q-axis component of flux is

$\Psi_q = \int (\upsilon_q - R_s i_q)\, dt$ (6)

From above two components the total flux is

$$\Psi_s = \sqrt{[\Psi_d^2 + \Psi_q^2]} \quad (7)$$

With the use of load angle (δ), the position of flux linkage (θ) can be estimated. Vectors of voltage are choosen based on the position of flux vector and with proper knowledge of δ [7]. Where δ is calculated as

$$\delta = \tan^{-1}\left(\frac{\Psi_d}{\Psi_q}\right) \quad (8)$$

Total torque using d and q-axis components is calculated as

$T_e = 3P(\psi_d i_q - \psi_q i_d)/2$ (9)

Hysteresis Comparator's of Flux and Torque

Claulated values of flux and torque are compared with the reference values. In the block the difference between these two are being compared[8]. Comparator will generate 1 if actual torque is lower than reference values else it will generate -1.

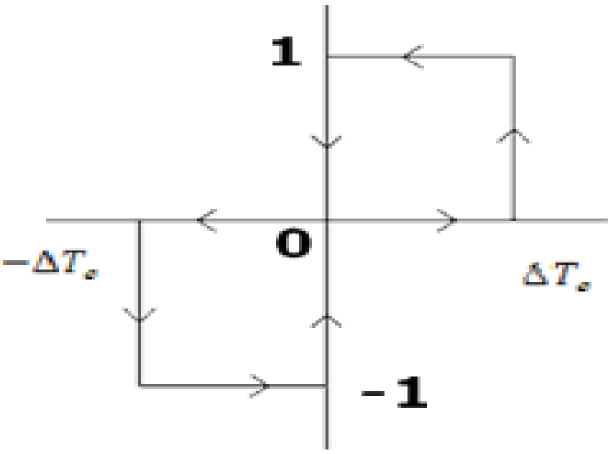

Figure 3.2 : 2-level torque hysteresis comparator

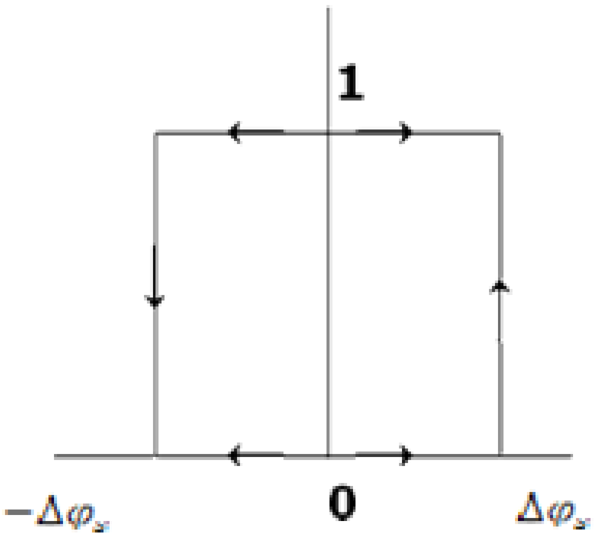

Figure 3.3: Two-level flux hysteresis comparator

In flux comparator the output of comparator will be 1 if actual flux is lower than reference else it will be 0.

Table for switching states

comparator states, φ, τ and θ are used to decide suitable voltage vector. Table of switching states is shown below. Through inverter the selected vector voltage is applied to motor.

Flux φ	Torque τ	θ -segment (Location of flux)					
		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
	τ = 1	V_1 1-1-1	V_2 11-1	V_3 -11-1	V_4 -111	V_5 -1-11	V_6 1-11
	τ = 0	V_0 -1-1-1	V_7 111	V_0 -1-1-1	V_7 111	V_0 -1-1-1	V_7 111
	τ = -1	V_5 -1-11	V_6 1-11	V_1 1-1-1	V_2 11-1	V_3 -11-1	V_4 -111
φ=1	τ = 1	V_2 11-1	V_3 -11-1	V_4 -111	V_5 -1-11	V_6 1-11	V_1 1-1-1
	τ = 0	V_7 111	V_0 -1-1-1	V_7 111	V_0 -1-1-1	V_7 111	V_0 -1-1-1
	τ = -1	V_4 -111	V_5 -1-11	V_6 1-11	V_1 1-1-1	V_2 11-1	V_3 -11-1

Table 3.1: Eight voltage vector table of Inverter 3.5.Voltage source Inveretr(VSI)

This will generate the voltages by the use of table. Operation of inverter is quite simple in this technique as this does not need any modulation technique. Voltage taken as source for the inverter.

3.6 Simulation:

Measured values of flux, torque were compared reference values in comparator. Outputs of these comparators along wth section number are used to select exact voltage which reduces the errors of flux,torque which are done through simulation diagram shown in figure 3.4.

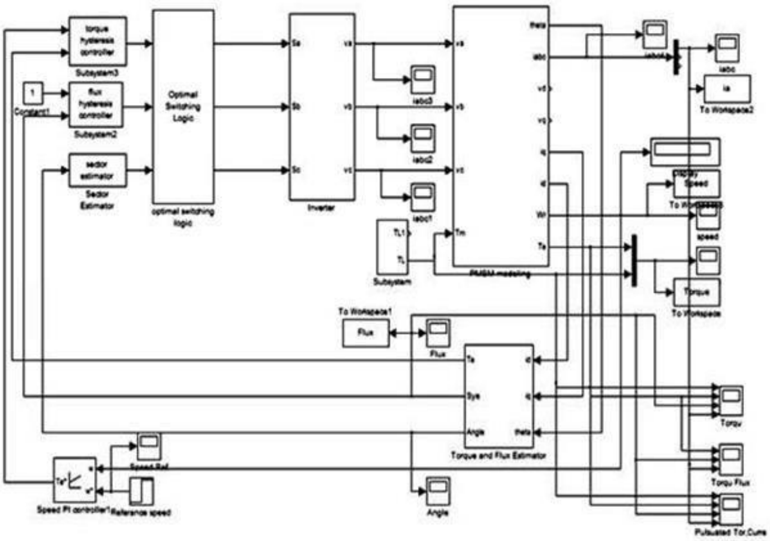

Fig 3.4 Matlab Block of DTC for PMSM.

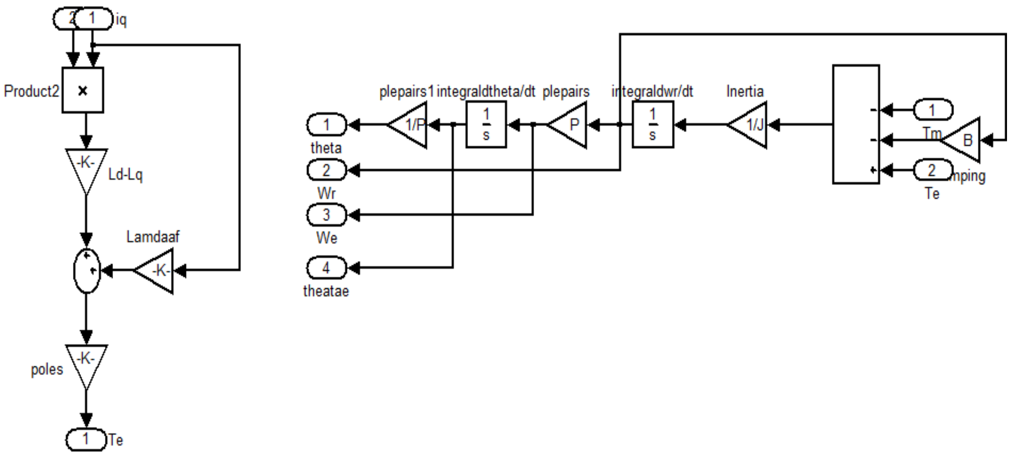

Fig 3.5: Block of Torque and Mechanical System of Equations

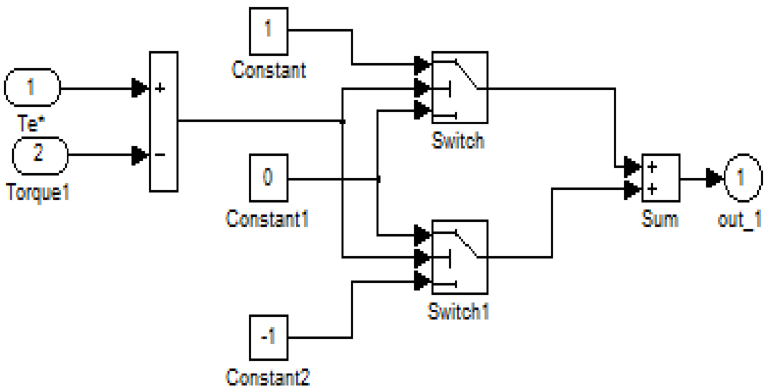

Figure 3.6: Torque Hysteresis implementation

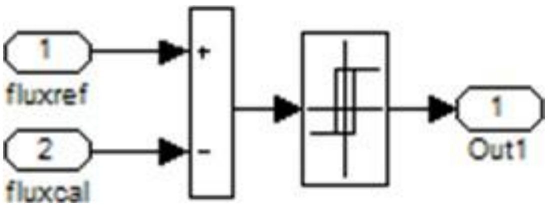

Figure 3.7: Flux Hysteresis implementation

4. RESULTS:

Parameters used in the simulation are: Resistance R_S(ohm)= 2.875Ω, Inductance [L_d,]H=0.185 H, Inductance [L_q,]= 0.069H,
Flux Induced by magnets=0.175, Inertia[Jkgm^2]=0.0008, Friction factor=0.0001.

4.1. The DTC performance of PMSM with Reference Torque is 2NM and Rated Flux Linkage is 0.5Web

Reference value of torque is taken as 2NM and for flux it is 0.5Web. Waveforms of torque, flux and currents which evaluate DTC for PMSM are shown.

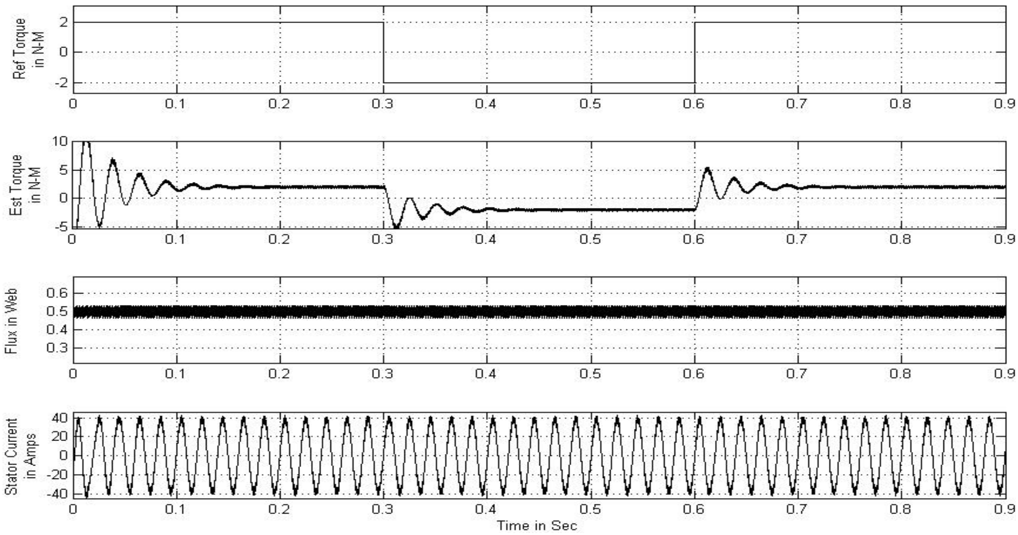

Figure 4.1: The Waveform of Reference Torque, Developed Torque, Stator flux linkage, Stator Current of the PMSM. Refence torque corresponding -2NM to 2NM , 0.5 Web flux linkage

Figure 4.1 explains that torque, flux's are alost on their correct values with few ripple content. Torque waveform settled at -2NM to2NM and flux waveform settled at 0.5 Web. Harmonics are present in the current waveform and it is settled between -40 to 40 Amps.

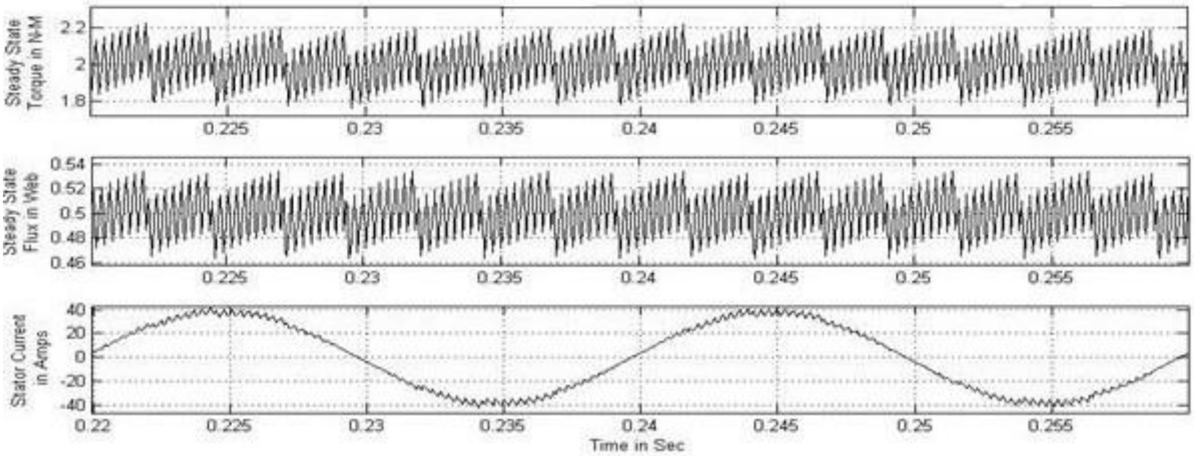

Figure 4.2: Developed Torque, Stator flux linkage, Stator Current. Refence torque corresponding -2NM to 2NM, 0.5Web flux linkage in Steady State Condition.

Figure 4.2 shows the torque, flux are reaching exactly given values under steady state condition with fewer ripple. In torque waveform ripple content varies between 1.8NM to 2.2NM. In flux waveform ripple content varies between 0.47web and 0.53 web.

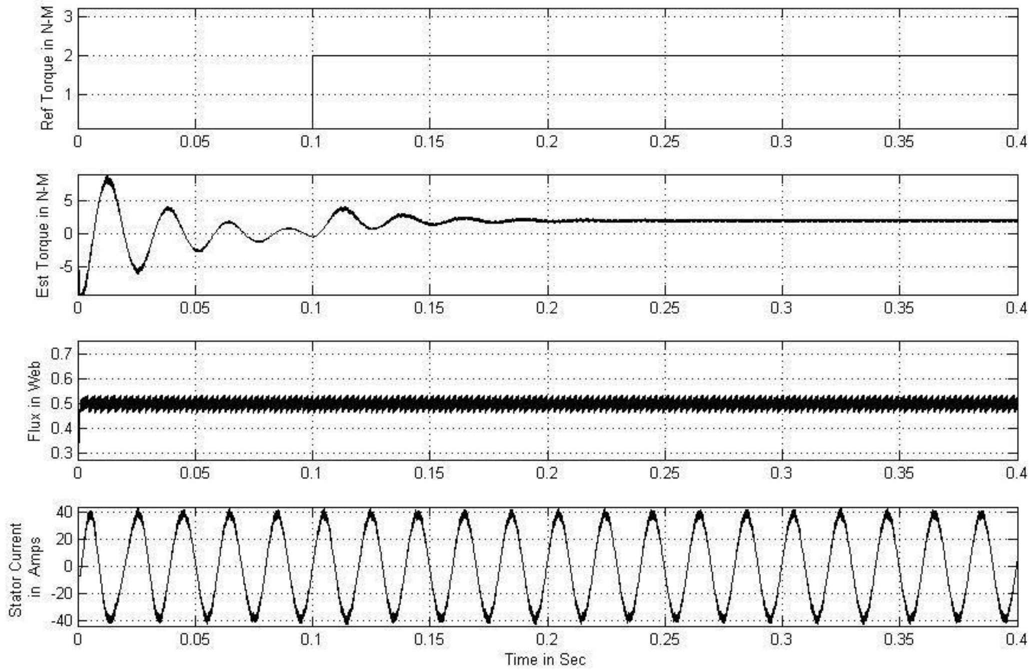

Figure 4.3: The Waveform of Reference Torque, Developed Torque, Stator flux linkage, Stator Current of the PMSM. Refence torque corresponding at 2NM with time delay of 0.1 sec and 0.5Web flux linkage.

Figure 4.3 shows the torque, flux's settles in final values with very low ripple. Torque waveform settled at 2NM and flux waveform settled at 0.5 Web. Harmonics are present in the current waveform and it is settled between -40 and 40 amps.

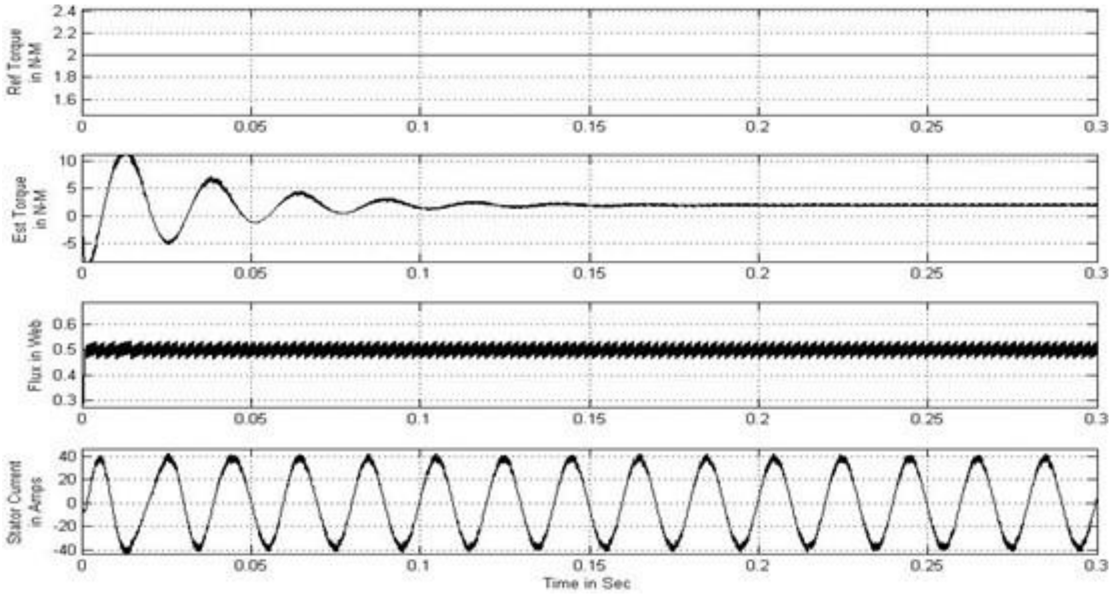

Figure 4.4: The Waveform of Reference Torque, Developed Torque, Stator flux linkage, Stator Current of the PMSM. Tref at 2NM with no time delay and 0.5Web flux linkage.

Figure 4.4 shows the torque, flux's settles in final values with very low ripple. Torque waveform settled at 2NM and flux waveform settled at 0.5 Web. Harmonics are present in the current waveform and it is settled between -40 to 40 Amps.

5. CONCLUSION

This paper has given many modeling equations of the machine. Analysis has given that torque can be varied by varying the speed of flux vector by maintaining the amplitude as same. With the proper selection of vectors of voltage using inverter the speed ad position flux vector can be varied. Introduction of DTC improved drives dynamic response with large robustness and fewer complexity. The Simulink block of DTC in PMSM is presented. Implementation of DTC to PMSM is analyzed under different conditions and this has given good response which is shown by all simulation results

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