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Direct Torque Control of Permanent Magnet Synchronous Motor

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***Abstract*: Direct torque control (DTC) is a method to control machine with utilizing torque and flux of motor controlled. In recent years Permanent Magnet synchronous motors (PMSMs) are used in many applications that require rapid torque response and high-performance operation. PMSM has no damper windings and excitation is provided by a permanent magnet instead of a field winding. The elimination of field coil, dc supply and slip rings reduce the motor loss and complexity.**

It is mathematically proven 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. This is achieved by using direct torque control (DTC) technique. This paper introduces the principle of space vector pulse width modulation (SVPWM) ,and closed loop speed control technique namely Direct Torque Control for Permanent Magnet Synchronous Motor Drive.

***Keywords:* Direct torque control (DTC), Permanent Magnet synchronous motors (PMSM), Space Vector Pulse Width Modulation (SVPWM).**

I. INTRODUCTION

Permanent magnet synchronous motor has been extensively developed due to their high power density and good dynamic performance, easy manufacture, low cost, high efficiency and reliance [5]. There are two competing control strategies for AC motors i.e. vector control (VC) and direct torque control (DTC). Almost 30 years ago, in 1971 field-oriented control (FOC) was proposed for induction motors. On comparing with traditional field oriented control, DTC does not required coordinate transform, pulse width regulator and position encoder, so its control strategy and control structure are simple. As the technology is improved, studies on PMSM such as direct torque control method have been improved as well. DTC has many advantages such as faster torque control, high torque at low speeds, and high speed sensitivity. Permanent magnet synchronous motors (PMSM) are widely used in low and medium 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. Simulations have helped the process of developing new systems including motor drives, by reducing cost and time. 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.

II. MODELLING OF PMSM

The Permanent magnet synchronous motor (PMSM) is a important category of the electrical machines. In this motor permanent magnets are attached to the rotor and magnetization is created in rotor. There are many mathematical models have been proposed for different applications, such as the *abc*-model and the two axis *dq*-model. Due to the simplicity of the two axis *dq*-model, it becomes the most widely used model in PMSM engineering controller design [7]. PMSM can be expressed as the following equations: The two axes PMSM stator windings can be considered to have equal turn per phase. The rotor flux can be assumed to be concentrated along the d axis while there is zero flux along the q axis. The stator flux linkage vector ψs and rotor flux linkage ψf of PMSM can be drawn in the rotor flux (dq), stator flux (xy), and stationary (DQ) frames as shown in figure 1 and 2

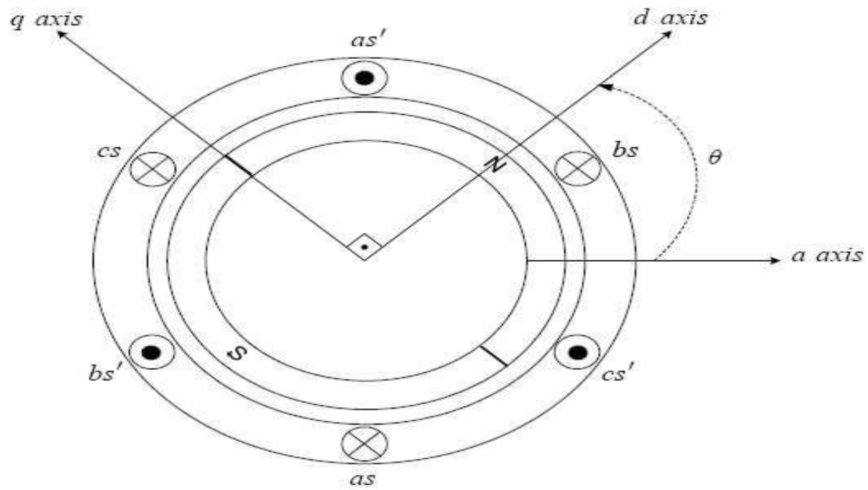

Fig.1.Two pole three phase surface mounted PMSM

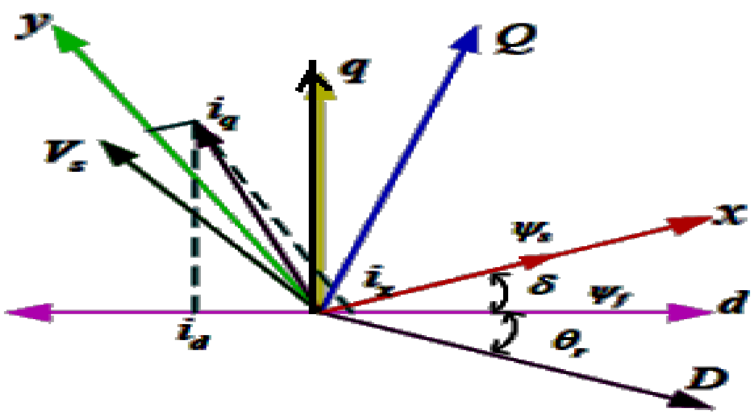

Fig.2.The Stator and rotor flux linkage in different frames

For dynamic model of PMSM, the assumptions made are spatial distribution of magnetic flux in air gap should be sinusoidal, and magnetic circuit should be linear (hysteresis and eddy current losses are negligible). The stator flux reference frame in D axis is in phase with stator flux linkage space vector *Ψ*s. Q axis (of SRF) leads 90^0 to D axis in CCW direction

$\omega r = d\theta_r/dt$ (1)

$\theta_s = \theta_r + \delta$ (2)

θ_s = rotational angle of stator flux vector,

θ_r = rotational electric angle of rotor,

$\Psi_s = L_s i_s + \Psi_{af} e^{j\theta r}$ (3)

Where L_s is stator self-inductance and Ψ_{af} is the rotor permanent magnet flux linkage. The stator voltage equation in rotor reference frame (dq reference frame) are given as

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$V_d=R_d i_d+d\Psi_d/dt- \omega_r\Psi_q$ (4)

$V_q=R_q i_q+d\Psi_q/dt- \omega_r\Psi_d$ (5)

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

$\Psi_q=L_q i_q$ and $\Psi_d=L_d i_d+\Psi_f$ (6)

Ψ_f is the flux through stator winding due to permanent magnets. Equivalent circuit of PMSM can be drawn as

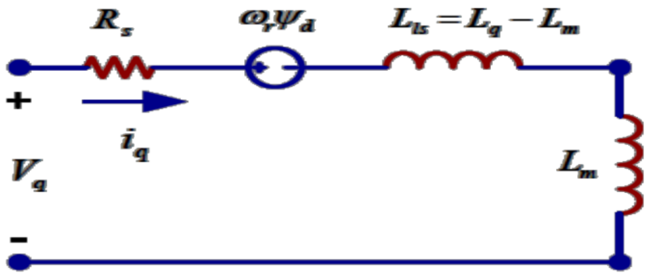

Fig.3 Equivalent circuit of PMSM d- axis

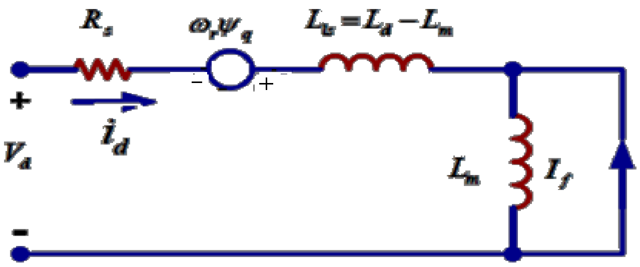

Fig.4 Equivalent circuit of PMSM q- axis

The developed torque motor is being given by

T_e =1.5P (Ψ_d i_q – Ψ_q i_d) (7)

The mechanical Torque equation is

T_e =T_L+ Bω_r+ J dω_m/dt (8)

Where T_L is load torque, J is moment of inertia, B (viscous friction) is damping coefficient. ω_r is the rotor electrical speed where as ω_m is the rotor mechanical speed. Here P are total no. of poles Based on theory of dynamics the motion equation of PMSM. Converting the phase voltages variables V*abc* to V*qdo* variables in rotor reference frame

$$\begin{bmatrix} Vd \\ Vq \\ V0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\theta r & \cos(\theta r-\frac{2\pi}{3}) & \cos(\theta r+\frac{2\pi}{3}) \\ sin\theta r & \sin(\theta r-\frac{2\pi}{3}) & \sin(\theta r+\frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad (9)$$

III. VOLTAGE SOURCE INVERTER

Inverter converts dc power into ac power at desired output voltage and frequency. A voltage-source converter performs the voltage and frequency conversion in two stages: ac to dc as a first stage and dc to ac for the second stage. The three phase six-step inverter offers simple control and low switching loss, lower order harmonics are relatively high resulting in high distortion of the current wave. Different PWM techniques can be used which are

- Single pulse width modulation.
- Multiple pulse width modulation.

- Sinusoidal- pulse width modulation.
- SV- PWM.

The Space Vector Pulse Width Modulation of a three level inverter provides the additional advantage of superior harmonic quality and larger under-modulation range that extends the modulation factor to 90.7% from the traditional value of 78.5% as in Sinusoidal Pulse Width Modulation case.

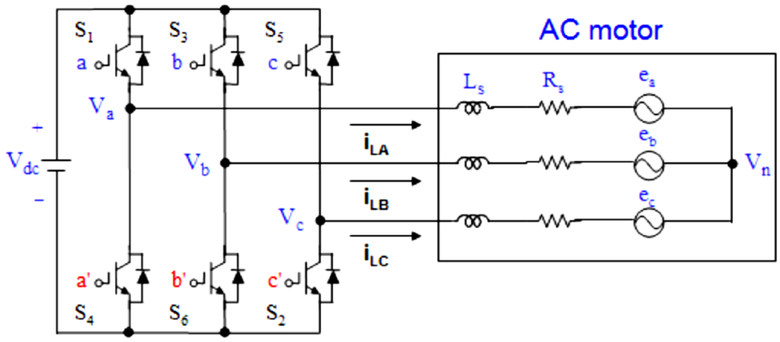

Fig.5 SVPWM- Inverter

S1 to S6 are the six power switches that shape the output, which are controlled by the switching variables a, a′, b, b′, c and c′. When an upper IGBT is switched on, i.e., when a, b or c is 1, the corresponding lower transistor is switched off, i.e., the corresponding a′, b′ or c′ is 0. Therefore, the on and off states of the upper transistors S1, S3 and S5 can be used to determine the output voltage. The relationship between variable vector [a,b,c] and the line to line voltage vector[VabVbcVca] is the given by

$$\begin{bmatrix} Vab \\ Vbc \\ Vca \end{bmatrix} = Vdc \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \qquad (10)$$

SVPWM generate a voltage vector that is close to the reference circle through the various switching modes of inverter.

V (SA, SB, SC) = 2Vdc(SA+ α SB+α^2 SC) / 3 (11)

Where $S_A(t)$, $S_B(t)$ and $S_C(t)$ are used as the switching functions for the three phases and Vdc is the dc bus voltage of inverter and α =$e^{j120.}$ The eight on-off states of inverter are listed in Table 1

Table-I ON-OFF states of Inverter

Inverter state	S_A S_B S_C	S_{A-} S_{B-} S_C	V_A/V_{DC}	V_B/V_{DC}	V_C/V_{DC}
0	000	111	0	0	0
1	001	110	-1/3	-1/3	2/3
2	010	101	-1/3	2/3	-1/3
3	011	100	-2/3	1/3	1/3
4	100	011	2/3	-1/3	-1/3
5	101	010	1/3	-2/3	1/3
6	110	001	1/3	1/3	-2/3
7	111	000	0	0	0

T refers to the operation times of two adjacent non-zero voltage space vectors in the same zone. Both V0(000) and V7(111) are called the zero voltage space vector, and the other six vectors are called the effective vector with a magnitude of 2Vdc/3.

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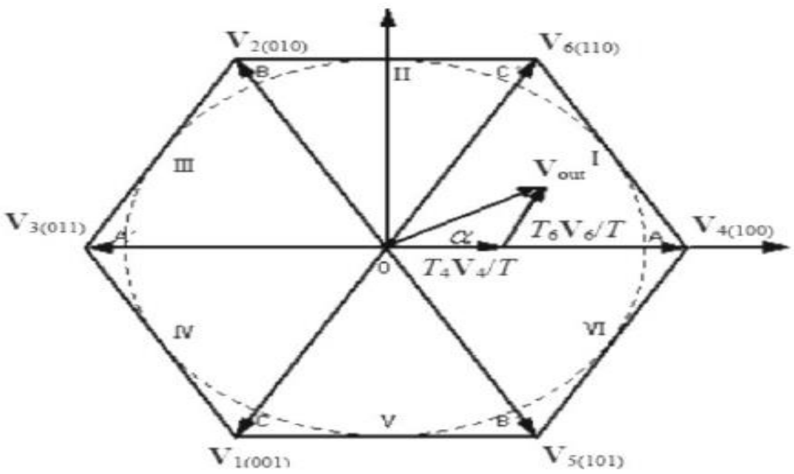

Fig. 6 voltage space vector

SV-PWM because on principal of it can be implemented by using sector selection algorithm, carrier based space vector algorithm, reduced switching or reduced switching carrier based SVM Sector Selection Based Space vector modulation. Based on the principle of SVPWM, the simulation models for generating SVPWM waveforms mainly include the sector judgment model, calculation model of operation, time of fundamental vectors, calculation model of switching time, and generation model of SVPWM waveforms.

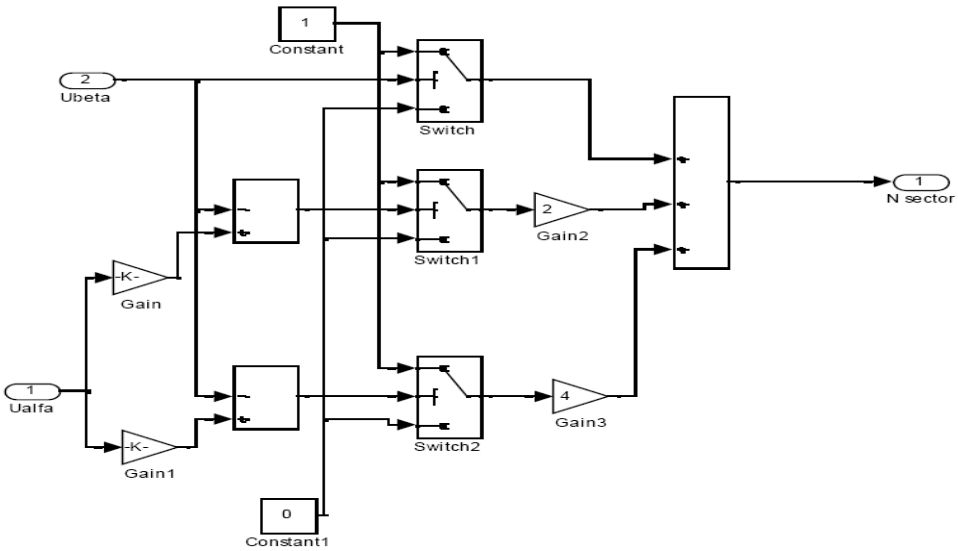

Fig.7 Simulink model of sector judgment

To determine the sector which the voltage vector is within, considering that the expression of vector in the α-β coordinate is suitable for controlling implementation,

when $V\beta > 0$, $A = 1$

when $\sqrt{3}\, V\alpha - V\beta > 0$, $B = 1$

when $\sqrt{3}\, V\alpha - V\beta < 0$, $C = 1$

Then, the sector containing the voltage vector can be decided according to N = A+2B+4C

For calculation of operation times of fundamental vectors against N, where T1 and Tm refer to the operation times of two adjacent non-zero voltage space vectors in the same zone.

$X = 1.732\ T\ V_{\beta}/(V_{dc})$, (12)

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$Y=1.5\,T(V_\alpha+0.5\,V_\beta)/(V_{dc})$, (13)

$Z=1.5\,T(-V_\alpha+0.5\,V_\beta)/(V_{dc})$ (14)

The relation between N and switch operation times is shown in Table II

$T_a=(T-T_1-T_m)\,/\,4$ (15)

$T_b=T_a+T_1/2$ (16)

$T_c=T_b+T_m/2$ (17)

Where T_{cm1} , T_{cm2} and T_{cm3} are the operation times of the three phases respectively.

Table-II Relation between N, Tcm, Ta, Tb, Tc

N	1	2	3	4	5	6
$T_{cm}1$	T_b	T_a	T_a	T_c	T_c	T_b
$T_{cm}2$	T_a	T_c	T_b	T_b	T_a	T_c
$T_{cm}3$	T_c	T_b	T_c	T_a	T_b	T_a

By comparing the computed Tcm1, Tcm2 and Tcm3 with the equilateral triangle, a symmetrical space vector PWM waveform can be generated. Fig. shows the simulink model for generation of SVPWM waveforms

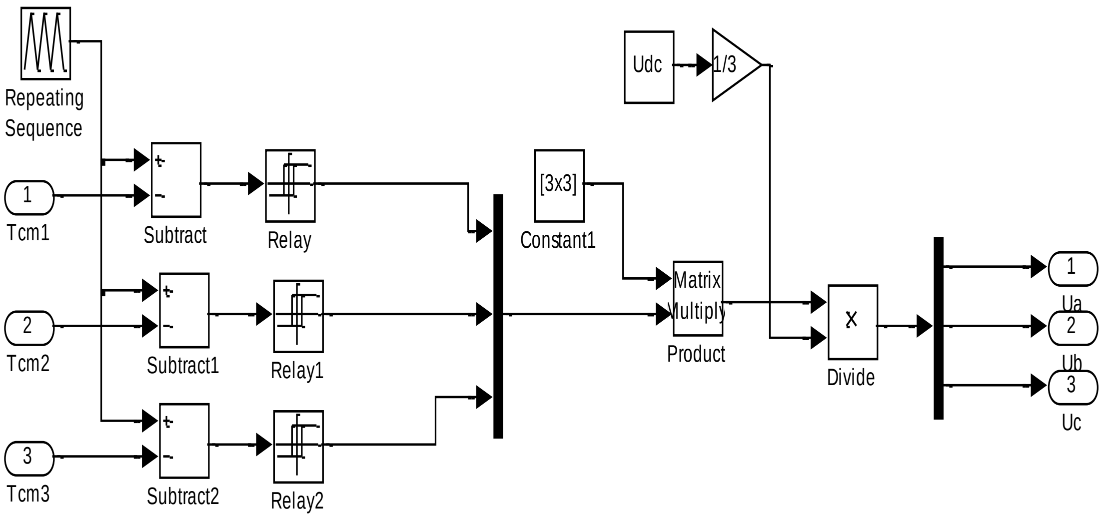

Fig.8 Generation of SVPWM waveforms

IV. DIRECT TORQUE CONTROL OF PMSM

DTC techniques are proving best optimized method for speed control of PMSM drive. Faster torque control, high torque at low speed & high speed sensitivity are some of the attributes of DTC. The main idea in DTC is to use the motor stator flux linkage & torque as basic control variables. In conventional method of speed control the rotor speed and angular position are sensed & feedback to control the speed of motor.

In PMSM increase of electromagnetic torque is directly proportional to the increase of the angle between stator and rotor flux linkages, consequently fast torque response can be achieved by adjusting the rotating speed of stator flux linkage. This is achieved by using DTC technique. The proposed system of DTC includes a flux & torque estimator which involves the three phase voltage measurement at input terminal of PMSM. In DTC the stator voltage vector are selected according to the difference between reference values & actual value of torque and stator flux linkage in order to reduce the torque and flux errors within the specified hysteresis band. The DTC require low computational power when implemented digitally.

The system possess good dynamic performance but shows quite poor performance in steady- state since the crude voltage selection criteria give rise to high ripple levels in stator current, flux linkage and torque. Its simplicity makes it possible to execute every computational cycle in a short time period and use a high sample frequency. For every doubling in sample frequency, the ripple will approximately halve. In the proposed DTC, the selection of voltage vector is achieved by the application of torque error, flux error and sectors. In this scheme, the estimated and reference flux value is obtained from the reference and estimated value of electromagnetic torque.

A better drive performance can be achieved by varying the duty ratio of the selected voltage vector during each switching period according to the magnitude of the torque error and position of the stator flux. In DTC method the control of electromagnetic torque & flux linkage is done directly & independently by using space vectors. In a PMSM if we neglect voltage drop due to stator resistance, variation of stator flux is directly proportional to applied stator voltage. Thus control of torque in PMSM can be achieved quickly by varying stator flux position (change in applied voltage to motor). DTC calculate & control stator flux linkage & torque of PMSM directly to achieve excellent transient performance.

In this proposed scheme, sensed speed is compared with the reference speed. The error signal is processed through a PI controller whose output is compared with the estimated value of torque. The steady state torque error is again processed through a PI controller, whose output is used as input to the optimal voltage estimator. The optimal voltage estimator will generate reference voltage Ualfa & Ubeta . By processing the torque error signal & estimated flux. The SV-PWM inverter is used to generate the three phase output voltage waveform, according to the reference signal i.e. in according to the speed of the PMSM drive. The figure shows the SVM-DTC scheme.

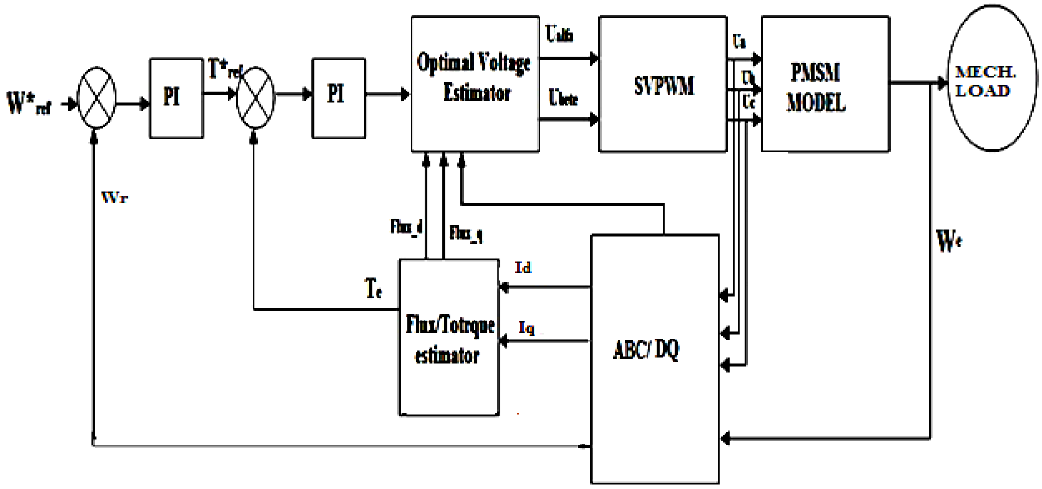

Fig.9 SVM-DTC scheme

Torque estimator is used to determine the actual value of the torque into this block enters the VSI voltage vector transformed to the q-d-stationary reference frame. The three-phase variables are transformed into d-q axes variables with the following transformation:

$$\begin{bmatrix} fd \\ fq \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & -1/3 & 1/3 \end{bmatrix} \begin{bmatrix} fa \\ fb \\ fc \end{bmatrix} \qquad (18)$$

The location of stator flux linkage (θ) is determined by the load angle (δ) i.e. the angle between the stator and rotor flux linkage. The load angle must be known so that the DTC can choose an appropriate set of vectors depending on the flux location. Flux linkage estimator estimates the flux.

This proposed DTC scheme uses three path closed loop control of speed, torque and flux linkage. PI controller is used to reduce steady state errors in all the three closed loop paths. The optimal voltage estimator has advantage of flux weakening control to reduce the ripples in torque and flux waves. In closed loop system sensed speed is compared with reference speed, and error is fed to PI controller, its output Te which is again compared with estimated Te in another closed loop. The torque error ΔTe is processed in a PI controller give output as δ which is angle between Ψaf and Ψs.

V. SIMULATION RESULTS AND ANALYSIS

The model of direct torque controlled permanent magnet synchronous motor (PMSM) drive is developed in MATLAB environment with Simulink & PSB tool boxes to simulate the behavior of drive with PI controller. These conditions are taken on the basis of with controller and without controller. In without controller the results are under DTC design. Performance of PMSM drive is tested under following conditions.

A. Performance of PMSM Drive with No Load Condition:

Fig 10 (A), (with svpwm controller) shows the simulated results of rotor speed and direct and quadrature axis (Id,Iq) winding current, for a speed reference of 500 rpm under no load condition i.e. TL=0 Nm and Fig 10 (B), (without svpwm controller) shows the simulated results of rotor speed and direct and quadrature axis (Id,Iq) winding current, for a speed reference of 500 rpm under no load condition i.e. TL=0 Nm. It is clear that the drive takes 50-60 m-sec to reach the set point speed. From the below figures it is also clear that the speed response has no overshoot oscillations which confirms the proper design of proposed direct torque control scheme.

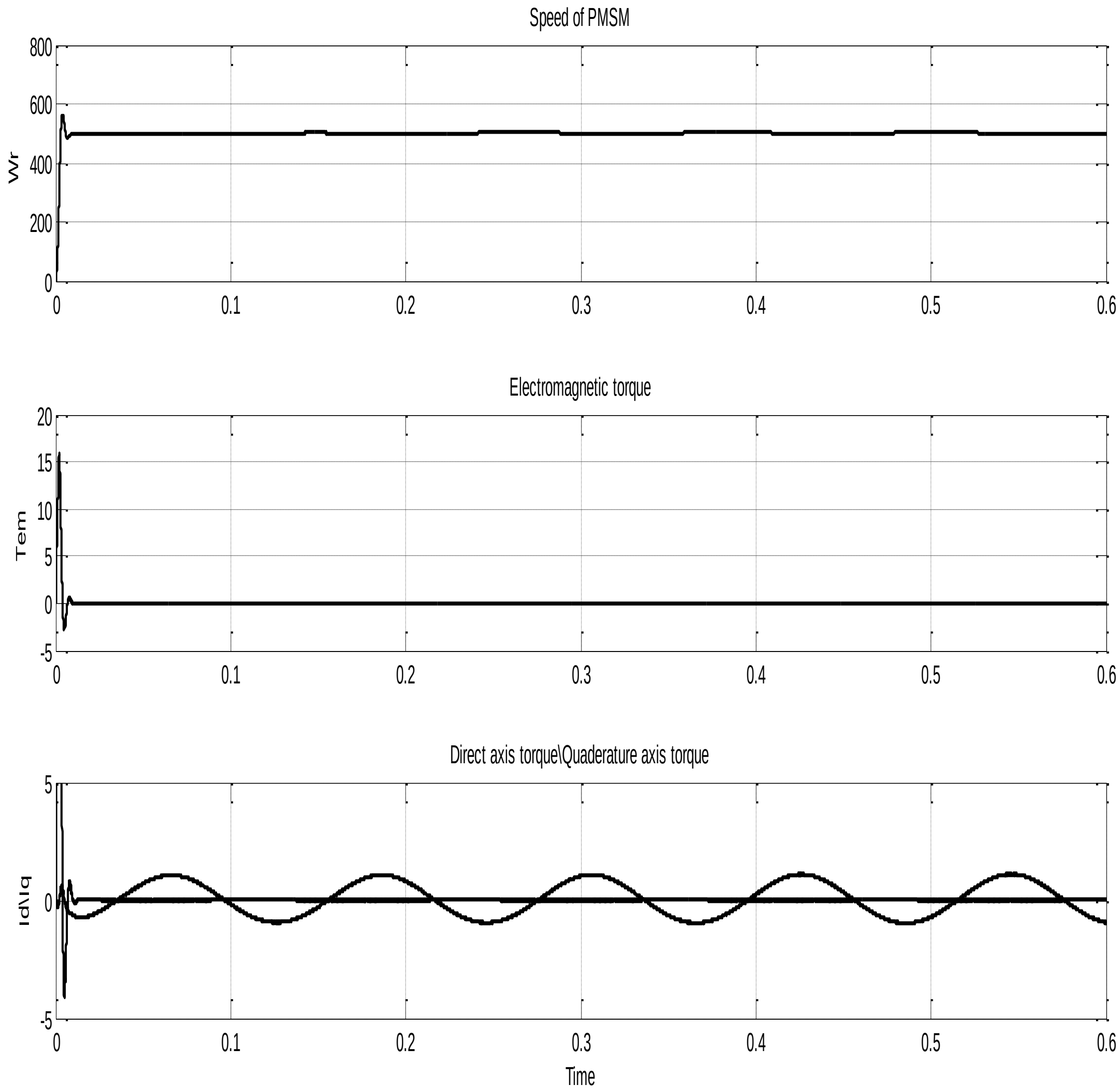

Fig-10(A) Speed of PMSM, Electromagnetic torque(in Nm),Direct and quadrature axis current Id, Iq in ampere

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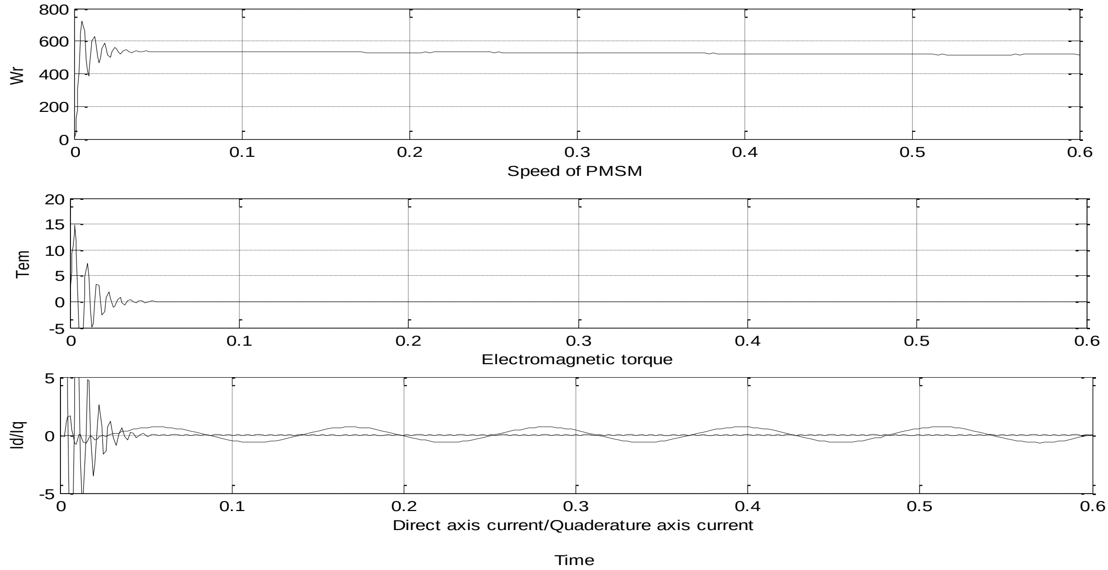

Fig-10 (B) Speed of PMSM, Electromagnetic torque (in Nm),Direct and quadrature axis current Id, Iq in ampere

B. Performance of PMSM Drive with Sudden Change in Load Torque:

Fig .11 (A), (with svpwm controller) shows the speed & torque response of Permanent magnet synchronous motors drive for a set speed of 500rpm with sudden change in load torque occurs at (t=0.1 sec) from 2 to 5 Nm and Fig .11 (B), (without svpwm controller) shows the speed & torque response of Permanent magnet synchronous motors drive for a set speed of 500rpm with sudden change in load torque occurs at (t=0.1 sec) from 2 to 5 Nm. (TL = 2 to 5Nm) the sudden application of load on the motor shaft cause a small dip in the rotor speed, which recovers quickly resulting in zero steady state speed error. An increased load on the shaft of the motor developing increased electromagnetic torque as indicating in fig 11(A) (with svpwm controller) and Fig 11(B) (without svpwm controller), the PI speed controller activated and recovers the rotor speed back to reference value under such load variation.

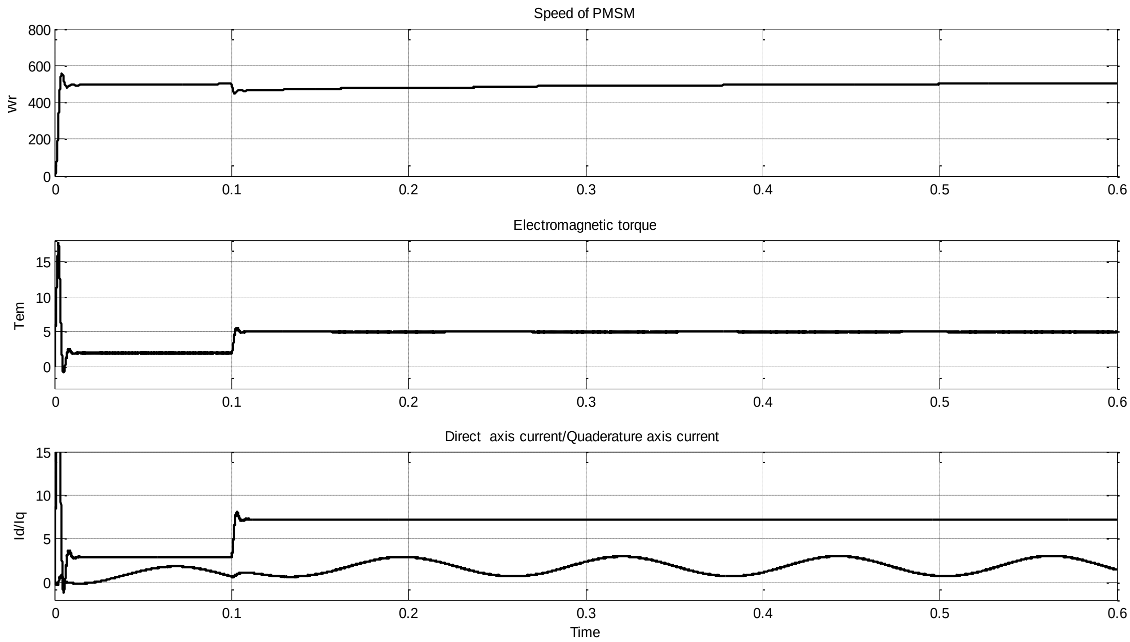

Fig11(A)speedof pmsm(rpm),electromagnetic torque(in Nm) current Id,Iq (in ampere)(for ωr=500 at t=0.1sec,TL= 2 to 5Nm)

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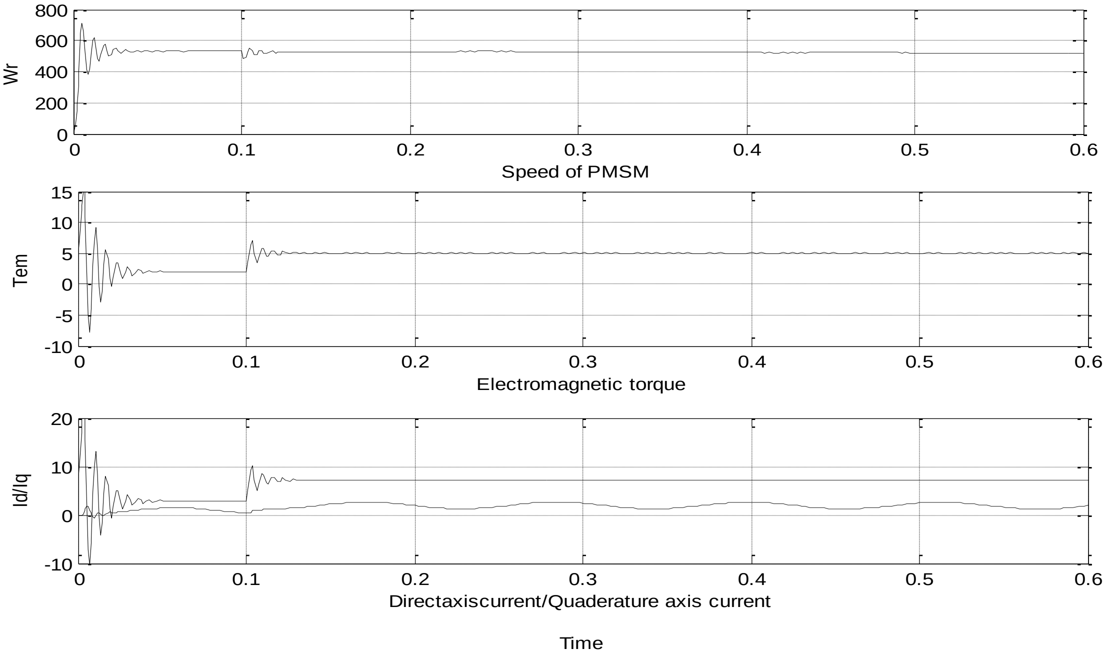

Fig11(B)speed ofpmsm(rpm),electromagnetic torque(in Nm),current Id, Iq (in ampere)(for ωr=500 at t=0.1sec,TL= 2 to 5Nm)

C. Performance of PMSM Drive under Speed Change:

Reference speed is changed from ω r = 800 to 250 rpm at t = 0.1 sec while the load torque is remained constant at TL =2 Nm. The response of motor speed, electromagnetic torque in the fig-12(A) (with svpwm controller) and fig(B)(without svpwm controller). It clear from fig that machine oscillations for a few cycle and finally settles to steady state reference value of ωr = 250 rpm. There is a dip in machine electromagnetic torque with sudden change in machine speed and it reaches to a value equal to the load torque very fast.

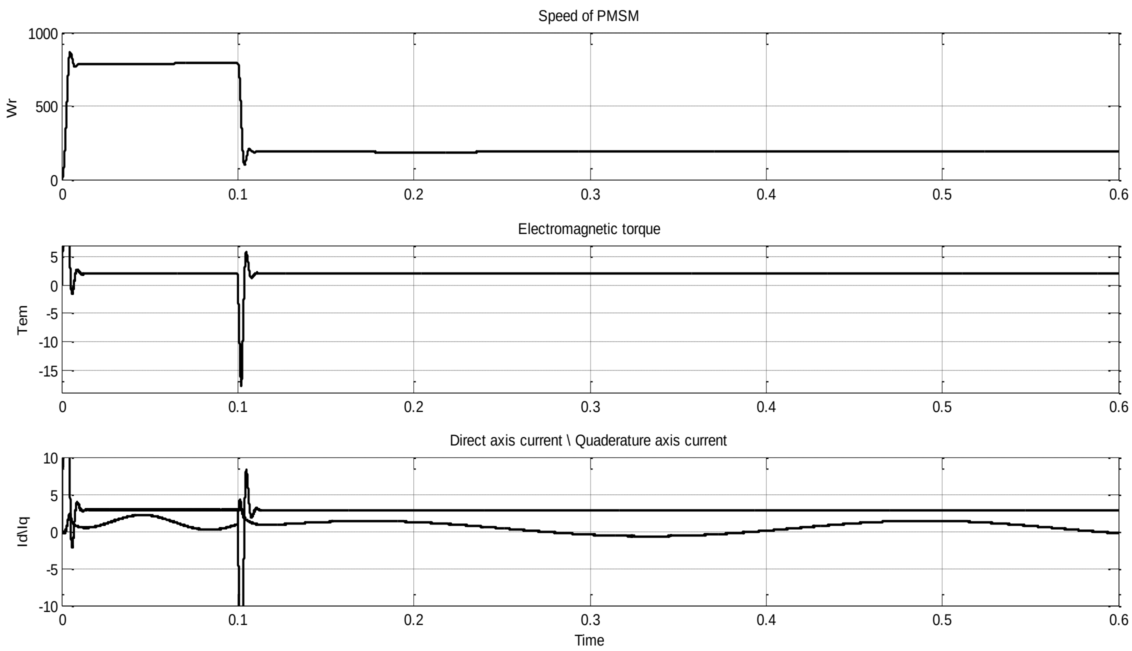

Fig-12(A) speed of pmsm(in rpm), electromagnetic torque (in Nm) current Id,Iq (in ampere), (for ωr=800 to 250 rpm at 0.1sec, TL=2Nm)

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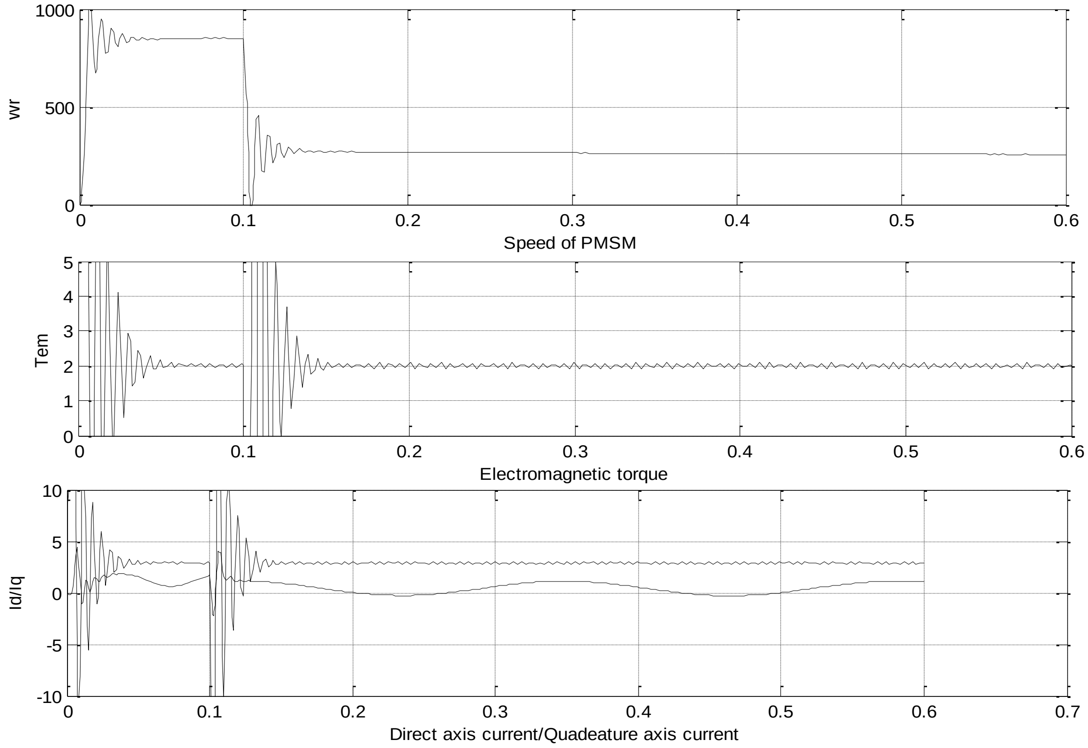

Fig-16 speed of pmsm(in rpm), electromagnetic torque (in Nm),current Id,Iq (in ampere), (for ωr=800 to 250 rpm at 0.1sec, TL=2Nm)

VI. CONCLUSION

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 space vector modulated inverter voltage vector in DTC. Speed control of PMSM drive system with direct torque control using Space vector modulated inverter technique is used for generating a desired value of pulses by using an appropriate value of switching frequencies. With the motor equations, a model for the PMSM has been developed in Simulink, as well as model of the space vector modulated inverter, and DTC are made. The results of the simulation show the good response of the model when tracking a command speed. Performance of 3-phase PMSM is investigated for the different load conditions and their comparison is also presented.

This paper presents the MATLAB/SIMULINK-based simulation model by adopting the classical double closed loops of speed, current and vector control method. The DTC technique is implemented with a SV-PWM inverter in both conditions with or without controller. In a SV-PWM inverter, the three levels in the phase voltage permit reduction of the harmonic content in stator voltages and currents and also in torque and flux ripples. The DTC as used for PMSM drive shows the excellent performance for both steady state as well as dynamic change in speed reference, and also with varying load conditions.

REFERENCES

[1] Narayan Prasad Gupta, Preeti Gupta (2012) “Performance Analysis of Direct Torque Control of PMSM Drive using SVPWM – Inverter” IEEE- IICPE,

[2] S .Dwivedi and B. Singh (2010) ‘Vector Control Vs Direct Torque Control Comparative Evaluation for PMSM Drive’ Senior Member, IEEE.

[3] Wang Z., Jin J., Guo Y. and Zhu J.(2008)‘SVPWM Techniques and Application in HTS Permanent Magnet Synchronous Motor Machine Control’ Journal of Electronics Science and Technology of China, Volume 6,No.2.

International Journal of Novel Research in Electrical and Mechanical Engineering
Vol. 2, Issue 2, pp: (25-36), Month: May - August 2015, Available at: www.noveltyjournals.com

[4] Ye X. and Zhang T.(2010)‘Direct Torque Control of Permanent Magnet Synchronous Motor using Space Vector Modulation’ IEEE Chinese Control and Decision Conference.

[5] Xiaoting Ye, Tao Zhang,@(2010) IEEE “ Direct Torque Control of Permanent Magnet Synchronous Motor Using Space Vector Modulation”.

[6] K.V. Kumar, P.A. Michael, J.P. John and Dr S.S. Kumar VOL 5,No 7 July(2010) ‘Simulation and comparison of spwm and svpwm control for three phase inverter’ ARPN Journal of Engineering and applied science.

[7] J. singh, B. Singh, S.P. Singh, Mohd Naim, R. Dixit ‘Performance and Evaluation of Drives Using DTC Technique’ IJRIC. April 2012 VOL 9.

[8] P. Ramana, B. S. Kumar, K.A. Mary, M.S. Kalavathi. ‘Direct Torque Control of Inverter Fed PMSM Drive Using SVM. Published in : IJAIEM VOL 2 Issue 7 July 2013.

[9] S. P. Chowdhury, “Mathematical Modeling and Performance evaluation of a Stand- Alone Polycrystalline PV plant with MPPT facility,” IEEE 2008

[10] Anguilar G., Dominguez A. and Maya R.(2010)‘Direct Torque Control of Permanent Magnet Synchronous Motor’ the IEEE Conf. Benemerita Universidad Autonoma De Pucbla,Maxico.

[11] Babu S.A.(2011)‘Direct Torque Control of Permanent Magnet Synchronous Motor’Published on International Journal Of Scientific & Engineering Research Volume 2, Issue 10, October

[12] B. K. Bose, Power Electronics and Variable Frequency Drives: Technology and Applications. IEEE Press, 1997