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MATLAB/SIMULINK MODEL OF FIELD ORIENTED CONTROL OF PMSM DRIVE USING SPACE VECTORS

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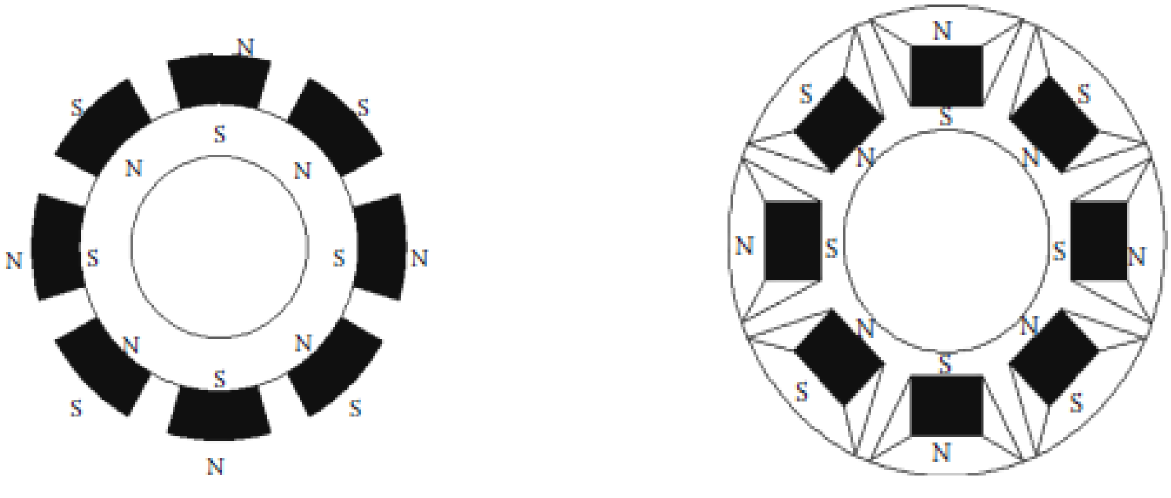
ABSTRACT

The permanent magnet synchronous motor (PMSM) drives have been frequently used as servo drives in many industrial applications. This paper presents a Matlab/simulink model of PMSM drive using field oriented control. This control technique is an advanced technique for speed and current control. The supply is provided through a three phase inverter where the switching is done by space vector pulse width modulation (SVPWM) technique. Compared to sinusoidal pulse width modulation SVPWM technique is preferred due to its better dc link utilization and less harmonic distortions in the output current. The model of PMSM drive using SVPWM is simulated and the results are analysed. Mathematical model of PMSM motor is done in d-q rotor reference frame.

KEYWORDS: *Permanent magnet synchronous motor, field oriented control, space vector modulation, PI controller.*

I. INTRODUCTION

Permanent magnet synchronous motor drives are becoming more popular in industries and are replacing induction motor drives due to their high performances: high torque density, high efficiency and small size. PMSM have no windings in the rotor instead they have rotating permanent magnets made of neodymium-boron- iron , Alnico or samarium cobalt that retain their magnetic property. The magnets can be mounted on the surface of the rotor for medium speed operations or placed internally inside the rotor for high speed operations as in figure 1.



(a) (b)

Figure 1. (a) Surface mounted permanent magnets (b) Permanent magnets placed inside.

In this paper surface mounted PMSM has been considered for which the air gap flux density is maximum. The three phase stator windings of the motor are excited by three phase currents fed from a three phase voltage source inverter. The field oriented control (FOC) or vector control of PMSM drive helps to decouple the torque and flux producing components of stator currents and hence, controlling the motor becomes easier like a DC motor. The type of control offers fast response and less torque ripple.

Unlike an induction motor, the only current that can be controlled in a PMSM drive is the three phase stator current, since there is no rotor winding current. The electronic switches in the three phase inverter are turned on and off to control the direction of current through the stator windings. The inverter switching pattern is based on space vector pulse width modulation (SVPWM) which is one of the best pulse width modulation techniques [2]. The SVPWM implementation method in [3], [4] and [5] is tedious and involves a lot of mathematical calculations. In this paper a simpler algorithm is implemented [6].The flux and torque ripples can be greatly reduced by this technique. Proportional and integral controllers have been used as speed and current controllers in the field oriented control of PMSM drive.

The field oriented control of PMSM deals with three reference frames namely the three phase stator reference frame, two phase stator reference frame and two phase rotor reference frame as in figure 2. Three phase stator reference frame (a-b-c) are 120 electrical degrees apart. Two phase stator reference frame (α-β) and three phase stator reference frame (a-b-c) are coplanar but the angle between the two axes (α-β) is 90 degrees instead of 120 degrees. The axis ‘a’ is aligned with ‘α’ axis. Rotor reference frame (d-q), in which the d axis is along the rotor magnetic axis or along the flux vector of the rotor and the q axis is at 90 degrees to the d axis and rotates at the same speed as the rotor.

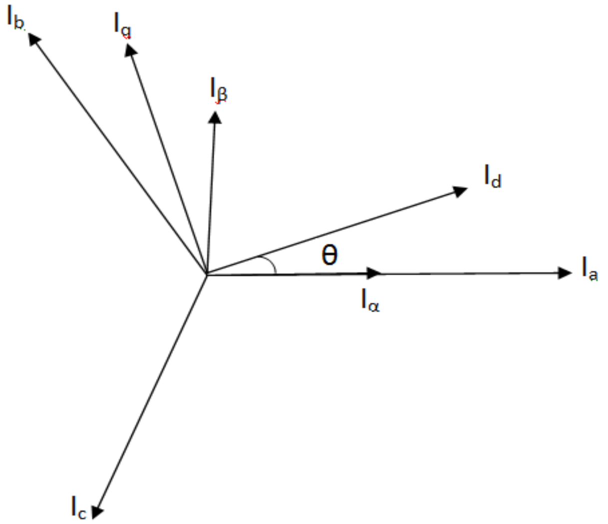


Figure 2. Representation of reference frames in FOC

The paper is organised as follows: Section II presents the mathematical model of PMSM and Section III describes the block diagram of field oriented control of PMSM drive. Section IV deals with the space vector pulse width modulation theory and the simulink model. The complete simulation model of the PMSM drive and the simulation results are presented in section V and the conclusion and future scope is discussed in section VI and VII respectively.

II. MATHEMATICAL MODEL OF PMSM

The PMSM motor has been modeled in d-q reference frame [1]. The rotor reference frame is chosen because the rotor position determines the instantaneous induced emf and subsequently the stator currents and torque developed in the machine. The following assumptions are made while developing the model [4].

- Sinusoidal mmf distribution in the stator windings.
- Space harmonics in air-gaps are neglected.
- Three-phase supply voltage is balanced.
- Saturation is neglected.

- The back emf is sinusoidal.
- Eddy currents and hysteresis losses are negligible.

The stator voltage equation in d-q reference frame is given by

$$V_q = R_q I_q + p\lambda_q + \omega_r \lambda_d \tag{1}$$

$$V_d = R_d I_d + p\lambda_d - \omega_r \lambda_q \tag{2}$$

The flux linkage equations are given by

$$\lambda_q = L_s I_q + L_m I_{qr} \tag{3}$$

$$\lambda_d = L_s I_d + L_m I_{dr} \tag{4}$$

Since the permanent magnet rotor flux is concentrated along d axis, the d axis rotor current (I_{dr}) is a constant and the q axis rotor current (I_{qr}) is assumed to be zero since there is no rotor flux along this axis.

$$\lambda_q = L_s I_q \tag{5}$$

$$\lambda_d = L_s I_d + L_m I_{dr} \tag{6}$$

Flux linkage established by permanent magnets is given by,

$$\lambda_m = L_m I_{dr} \tag{7}$$

Electromagnetic torque developed by the motor is given by,

$$T_e = \frac{3}{2}\frac{p}{2}\lambda_m I_q \tag{8}$$

Since the magnetic flux linkage is a constant, the torque is directly proportional to the q axis current. The electromagnetic torque equation is given by,

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \tag{9}$$

Hence rotor mechanical speed is given by,

$$\omega_m = \int\left(\frac{T_e - T_L - B\omega_m}{J}\right)dt \tag{10}$$

Rotor electrical Speed,

$$\omega_e = \omega_m \frac{p}{2} \tag{11}$$

The three phase stator reference frame variables (abc) are transformed into d–q reference frame by,

$$\begin{bmatrix} v_q \\ v_d \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \cos(\theta-120) & \sin(\theta-120) \\ \cos(\theta+120) & \sin(\theta+120) \end{bmatrix}\begin{bmatrix} V_q \\ V_d \end{bmatrix} \tag{13}$$

Transformation from two phase stator reference frame (α-β) to rotor reference frame (d-q) and vice versa by Park’s transformation and vice versa by inverse Park’s transformations

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} iq \\ id \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} iq \\ id \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad (15)$$

Three phase (abc) to two phase (αβ) transformation is done by Clarke's transformation.

$$\begin{bmatrix} v\alpha \\ v\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} va \\ vb \\ vc \end{bmatrix} \quad (16)$$

The mathematical model of PMSM is done in MATLAB/Simulink as given in figure 3.

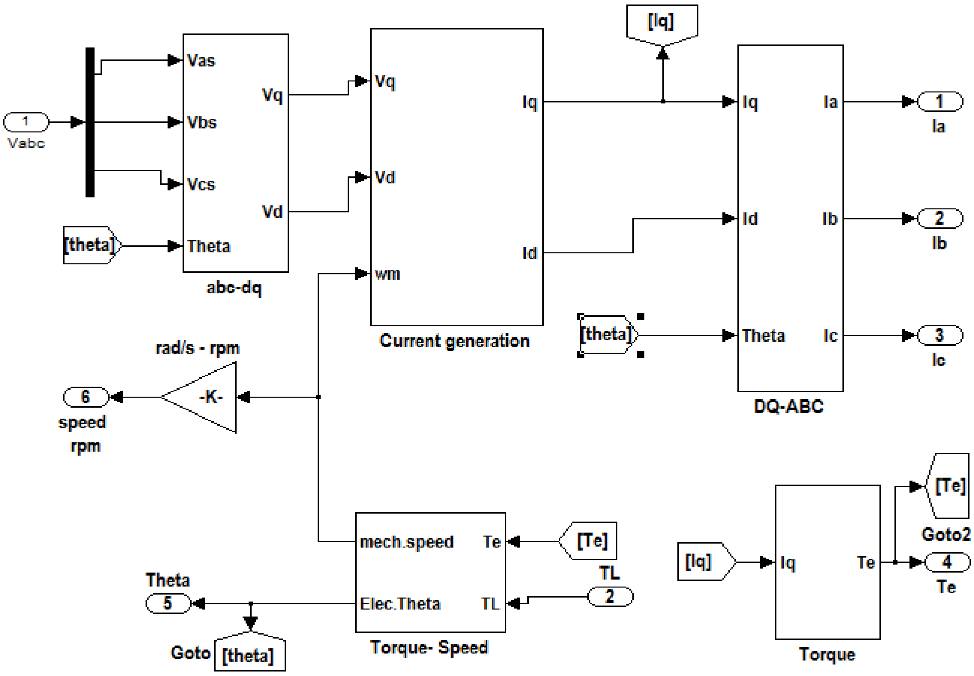


Figure 3. Modeling of PMSM in MATLAB/ Simulink

III. FIELD ORIENTED CONTROL OF PMSM

The block diagram of field oriented control (FOC) of PMSM is shown in figure 4 which has the decoupled torque and flux channels with feedback. The rotor position information is required for the FOC of the motor. This is provided by an encoder or resolver and speed is calculated from rotor position (θ). Motor speed is compared with reference speed and the error is fed as input to the PI controller whose output will be proportional to torque producing component of stator current (i_{qref}). This current is compared with q-axis component of stator current (i_q) and error is fed to another PI controller to find q-axis reference voltage component V_{qref}. The d-axis component of stator reference current which is the flux producing component (i_{dref}) is taken equal to zero to satisfy maximum torque per ampere condition. This current is compared with motor d-axis current component and the error is fed to PI controller to find V_{dref}.

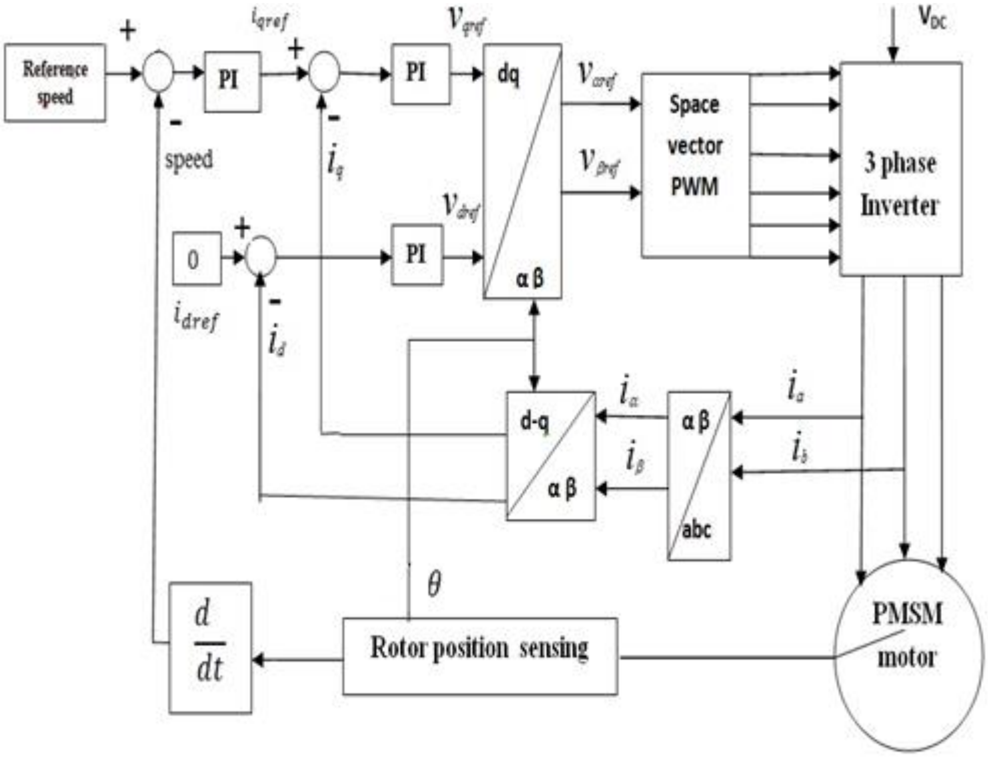


Figure 4. Block diagram of field oriented control of PMSM

IV. SPACE VECTOR PULSE WIDTH MODULATION

Three phase voltage source inverter has six switching devices which are turned on and off in a particular switching pattern to develop the required voltage across the stator windings of the PMSM drive. Two switches on the same leg of the inverter are never turned on simultaneously and also for a PMSM motor all the three stator windings are excited at any period of time. This will generate a sinusoidal back emf in a PMSM motor. Space Vector PWM technique has six active switching states and two zero (null) voltage states (0,0,0 and 1,1,1).The six active switching states are represented as voltage space vectors(V_1 to V_6) and the null vectors (V_0 and V_7) in the figure 5.The active vectors are 60 degrees apart and form six vertices of a hexagon and the null vectors are at the origin. There are six sectors for the hexagon and the required voltage, V_{ref} which is synthesized by finding in which sector it lies[2].

The reference voltage vector is generated by different operating times of null vector and adjacent vectors in the sector in which V_{ref} lies. For a sampling period, T_s, the operating time of active vectors and null vectors should satisfy the volt sec balance.

The v_{dref} and v_{qref}components of voltage is transformed into $v_{\alpha ref}$ and $v_{\beta ref}$ before fed as input to SVPWM block. The model of SVPWM generation block in MATLAB/ Simulink is shown in figure 6. The MATLAB function code implements the algorithm to generate pulses for SVPWM technique. The input will be the magnitude and angle of voltage reference and the switching time signal for comparison to generate the pulses shown in figure 8. The MATLAB code first identifies the sector in which reference voltage lies and then calculates the operating times of active and null vectors [3].

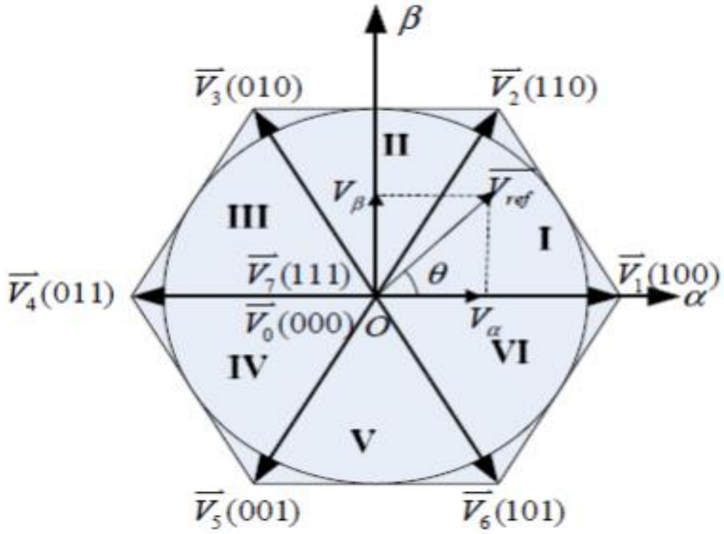


Figure 5. Space vector Modulation

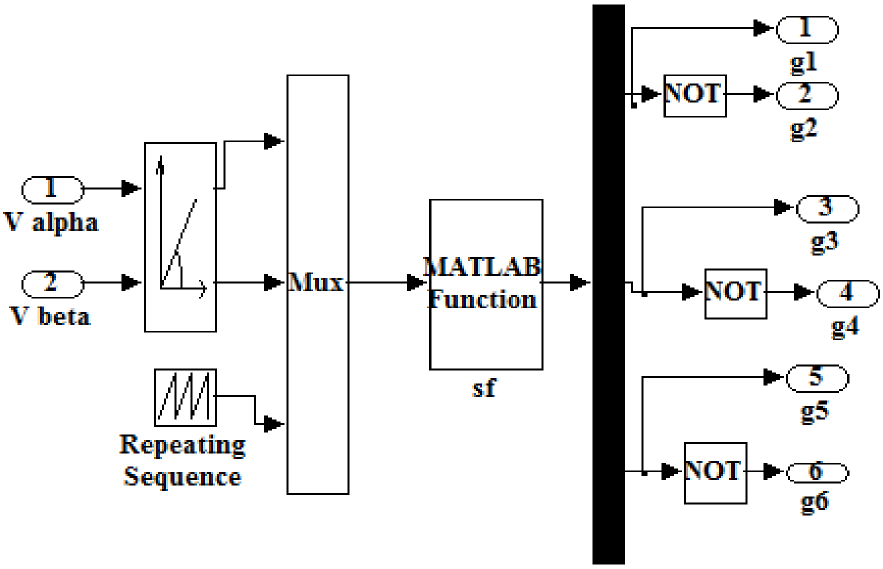


Figure 6. SVPWM Simulink Model

V. SIMULATION AND RESULTS

The simulation of PMSM drive is done in MATLAB/Simulink and the model is given in figure 7. The motor has been modelled as in figure 3 using the parameters given in Table 1.

TABLE I. MOTOR PARAMETERS

Parameter	**Value**
d axis inductance (L_d)	0.6 mH
q axis inductance (L_q)	0.6 mH
Stator resistance (R_s)	0.36 Ω
Motor Inertia(J)	0.006 wb
Number of poles (p)	8
Flux linkage established by magnets (λ_m)	48 gcm^2

The drive system consists of the motor model, three phase inverter fed by a 24 V dc supply. The firing pulses are provided by the SVPWM block and the switching frequency is taken as 5 kHz. Necessary transformation blocks and PI controllers are included in the simulation model. To check the model performance, different load and speed conditions are simulated and the results are given. When a constant load torque and constant reference speed of 4000 rpm is given the three phase currents generated are sinusoidal with minimum distortions, in figure 9. The torque and speed curves settle at their reference values before 0.01s, in figure 10. When a step change in load torque is given at 0.04s, the three phase currents shows the change in magnitude of current with change in torque (figure 11) and the motor continues to run at the given reference speed even after the change in load as in figure 12. The step change in speed from 4000rpm to 2000 rpm is shown in figure 13.

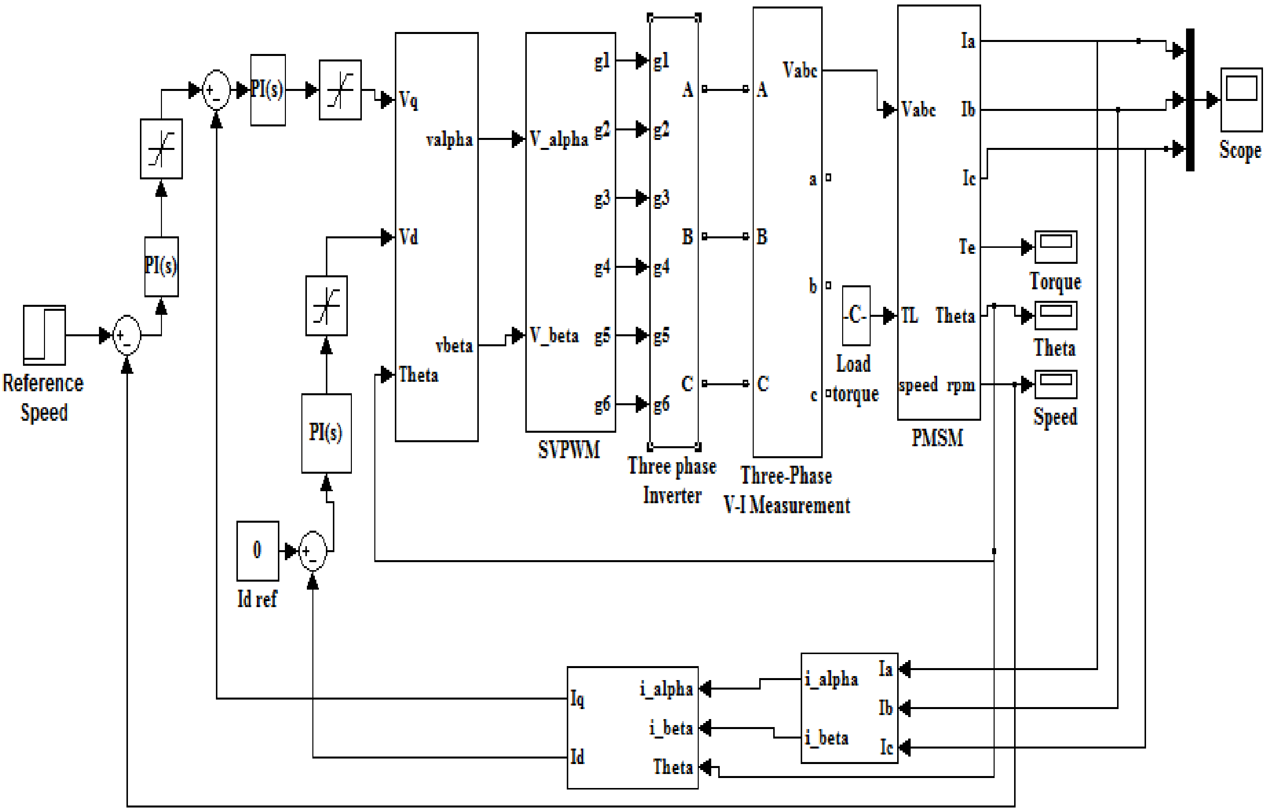


Figure 7. MATLAB/SIMULINK model of PMSM drive.

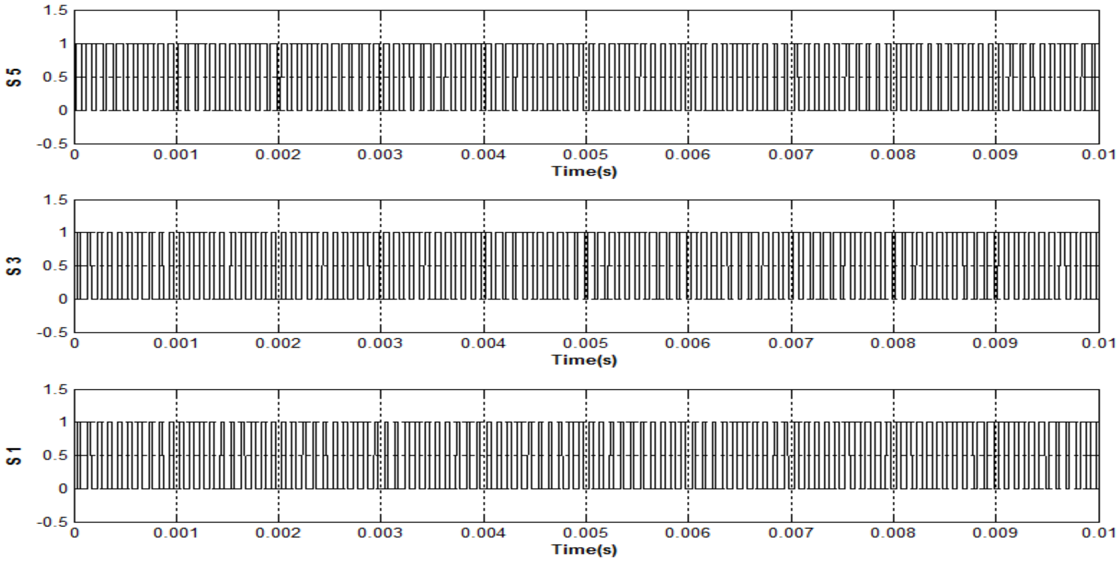


Figure 8. Inverter switching pulses of upper three switches with SVPWM

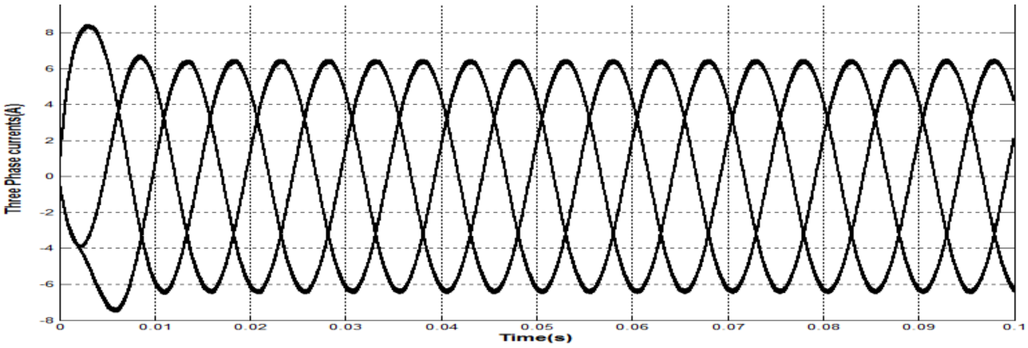


Figure 9. Three phase currents for a constant load torque

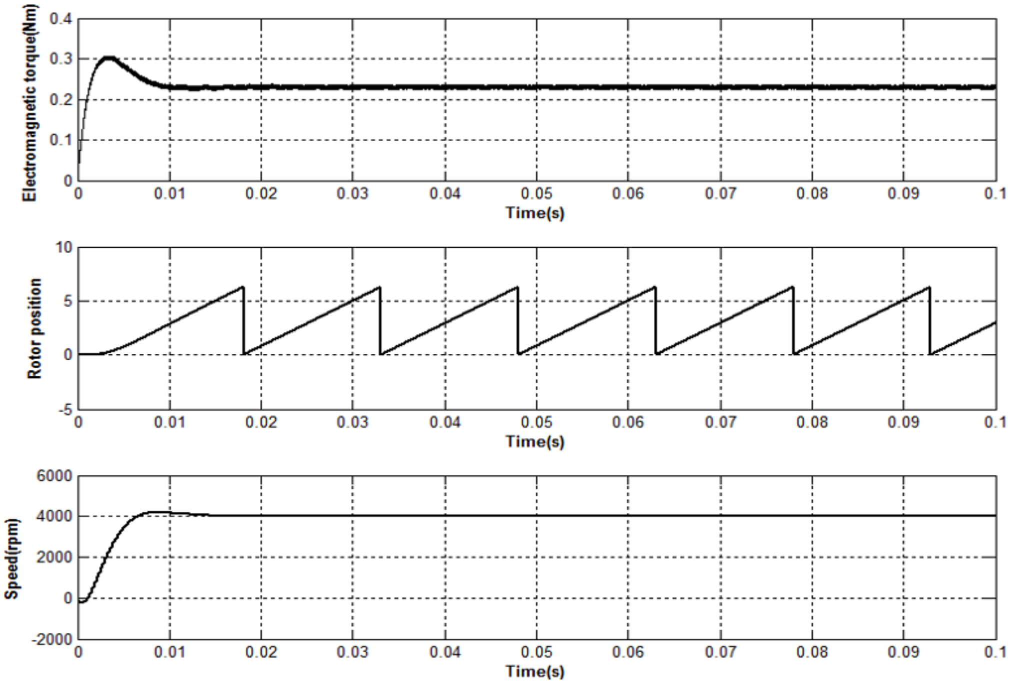


Figure 10. Torque, rotor position and speed curves

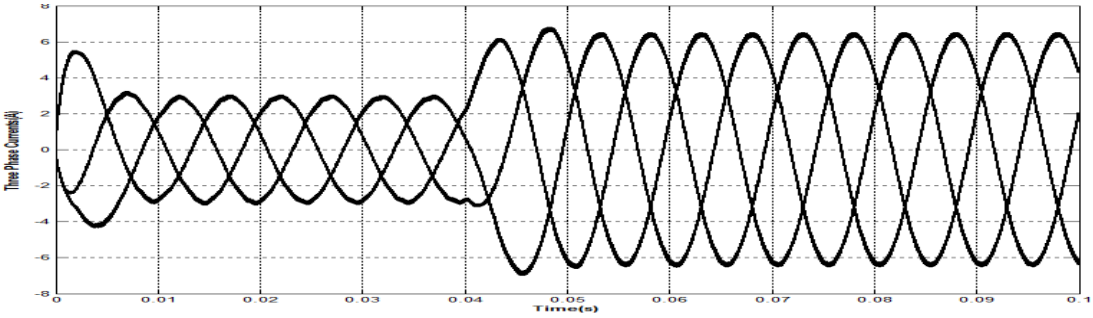


Figure11. Three phase currents for a step change in load torque at 0.04s

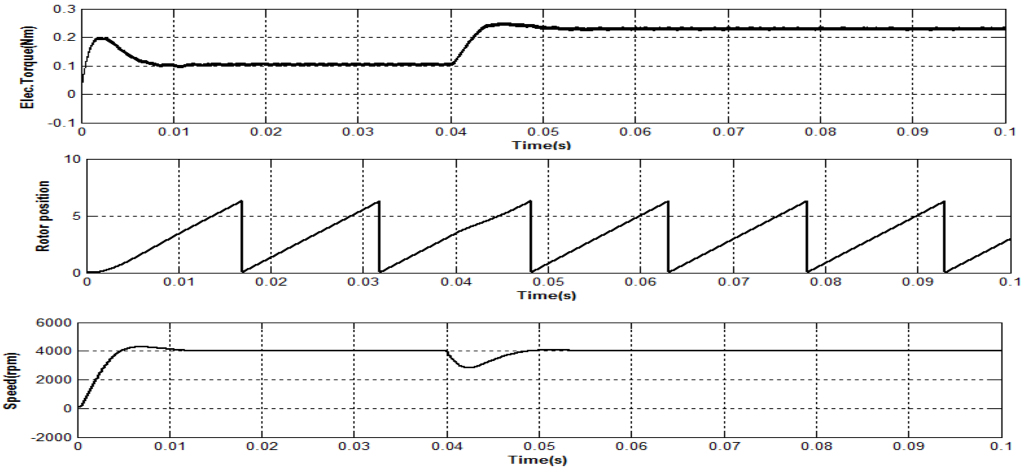


Figure 12. Torque and speed curve for step change in load torque at 0.04s

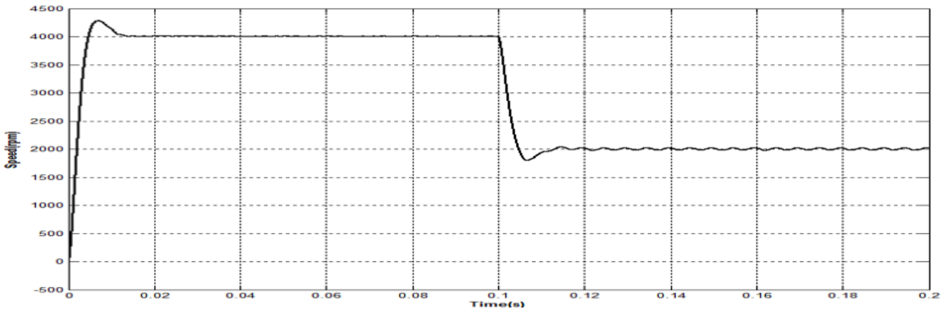


Figure 13. Speed curve for step change at 0.04s

VI. CONCLUSION

The modeling of PMSM drive and its field oriented control under different load conditions are simulated and the results are analysed. MATLAB/Simulink library provides easy modeling of PMSM drives and the simulated results will be helpful in hardware implementation of the drive. The transient and steady state values of current, speed and torque curves are analysed. The three phase currents show less distortion and torque curves have very little ripples. Thus SVPWM technique has the advantage of less overshoot, lower torque pulsation and quick response.

VII. FUTURE SCOPE

The future scope includes the reduction of current sensors by dc link current sensing using a single sensor and position sensorless control of PMSM drive by speed and position estimation.

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