International Journal of Emerging Engineering Research and Technology
Volume 2, Issue 3, June 2014, PP 246-255
ISSN 2349-4395 (Print) & ISSN 2349-4409 (Online)

Field Oriented Control of PMSM Drive using SVPWM Technique

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Abstract: *This paper focus on the advancement of SVPWM (space vector pulse width modulation) inverter fed permanent magnet synchronous motor (PMSM).The paper deals with a space vector pulse width modulation (SVPWM) algorithm applied to electrical drives. Anextensive and detailed study of the space vector pulse width modulation design process hasbeen done, that indicate some practical sign for implementation. As an example, the SVPWM is developed for a permanent-magnet synchronous motor drive for Speed and current control.In the present work, three closed loop control scheme has been used. Two inner loops are current control feedback loop and another outer feedback loop is used for optimizing the speed of PMSM drive. The proposed field oriented control (FOC) scheme for PMSM drive decouples the torque and flux which is not only providing the faster response but at the sometime makes the control action easy.*

Keywords: *FOC, MATLAB/Simulink, PMSM, speed control, SVPWM Inverter*

1. Introduction

Over the last three decades AC machine drives are becoming more and more popular, especiallyPermanent Magnet Synchronous Machine (PMSM)has been used in many automation fields such as robot, metal cutting machines, precision machining, etc. The PMSM drives are ready to meet sophisticated requirements such as fast dynamic response, high power factor, wide operating speed range and high performance applications, as a result, a gradual gain in the use of PMSM drives will surely be in the future market in low and mid power applications.Recently, PMSM is applied to traction drive for electric vehicles and railway vehicles. [1-2]

In the current control for an inverter-fed PMSM drive, there are four main types of control schemes; the hysteresis control, the ramp comparison control, the synchronous frame proportional-integral (PI) control, and the predictive control [3-7].

The hysteresis current controller has advantages such as a fast transient response and simplicity in implementation, but shows a high and non-constant switching frequency in the inverter. The ramp comparison current control method has the advantages of limiting the maximum inverter switching frequency and producing well-defined harmonics [3]. Even though the controller has optimized gains, there are magnitude and phase delay errors in steady state since, the control method has low pass filter characteristics. To overcome such errors, a rotor synchronous frame PI current control has been proposed. In this control method, the current control is carried out in rotor synchronous reference frame. In the SVPWM control scheme, the switching duties of the inverter switches are determined by calculating the required voltages forcing the motor phase currents to follow corresponding references. If the motor and inverter parameters are well known, the SVPWM inverter shows the fast transient response and no steady state error.

2. PMSM Modeling

The mathematical model is similar to that of the wound rotor synchronous motor. Since, there is no external source connected to the rotor side and variation in the rotor flux with respect to time is negligible, there is no need to include the rotor voltage equation. Rotor reference frame is used to derive the modal of the PMSM[9].

The electrical dynamic equation in terms of phase variable can be written as:

$$V_A = R_S i_A + p\psi_A \text{.......................................}(1)$$

$$V_B = R_S i_B + p\psi_B \text{.......................................}(2)$$

$$V_C = R_S i_C + p\psi_C \text{.......................................}(3)$$

Where, V_A, V_B and V_C are instantaneous phase voltage, i_A, i_B and i_C are instantaneous phase current, R_S is phase resistant, p is derivative operator, ψ_A, ψ_B and ψ_C are rotor coupling flux linkage.

While the flux linkage equation are:

$$\psi_A = L_S i_A + \psi_r \cos\theta \text{..................................}(4)$$

$$\psi_B = L_S i_B + \psi_r \cos\left(\theta - \frac{2\pi}{3}\right) \text{......................}(5)$$

$$\psi_C = L_S i_C + \psi_r \cos\left(\theta + \frac{2\pi}{3}\right) \text{......................}(6)$$

Where, L_S is phase Inductance.

The transformation from 3-phase to 2-phase quantities can be written in matrix form as:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \text{.............}(7)$$

Where, V_α and V_β are orthogonal space phasor.

The Park Transformation in matrix form can be represented as:

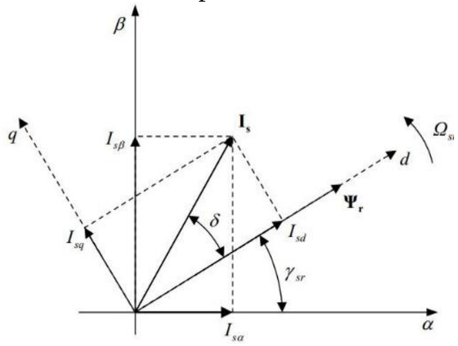

Fig.1: *Vector Diagram of PMSMMotor in Stationary α−β and Rotatingd−qCo-ordinates*

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \text{.....................}(8)$$

According to above transformation. $d - q / abc$ Transformation may be written as:

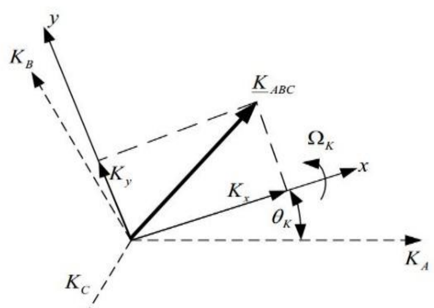

Fig.2. *Stator Fixed Three Phase Axes (A,B,C) and General Rotating Reference Frame*

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \text{...(9)}$$

Simple transformed equation are:

$$V_d = R_S i_d + pL_d i_d + p\psi_r - \omega_r \psi_q \text{.................(10)}$$

$$V_q = R_S i_q + pL_q i_q + \omega_r \psi_q \text{............................(11)}$$

Where, L_d and L_q are called d-and q-axis synchronous inductance respectively, ω_r is motor electrical speed.

The produced torque T_e which is power divided by mechanical speed can be represented as:

$$T_e = \frac{3}{2} p_n \left(\psi_r i_q + (L_d - L_q) i_d i_q \right) \text{...................(12)}$$

Where, p_n is pole Logarithm.

It is apparent from the above equations that the produced torque is composed of two distinct mechanisms. The first term corresponds to ‘‘the mutual reaction torque’’ occurring between i_q and the permanent magnet, while the second term corresponds to ‘‘the reluctance torque’’ due to the difference in d- and q-axis reluctance [9]. Note that $L_d = L_q = L_s$ for the motor, so an expression for the torque generated by a PMSM is:

$$T_e = \frac{3}{2} p_n \psi_r i_q \text{..(13)}$$

In the presence of a *d*-axis stator current, the *d*-axis and *q*-axis currents are not decoupled, and the model is nonlinear. It has been shown in the torque Eq. (12). Under the assumption that id= 0, the system becomes linear and resembles, Thus vector control of PMSM provides approximate desired dynamic characteristics.

In general, the mechanical equation of the PMSM can be represented as

$$T_e = J_M \omega_M + T_d + B_M \omega_M \text{............................(14)}$$

Where,

ω_M = rotor angular speed,

J_M = motor moment inertia constant,

B_M = damping coefficient,

T_d = torque of the motor external load disturbance,

T_e = electromagnetic torque.

3. SPACE VECTOR PULSE WIDTH MODULATION (SVPWM)

The SVPWM consists of four major process:

i. Sector Identification,
ii. Vector action time,
iii. Computation of switching time
iv. Generation of PWM,

Fig.5 showing the process of generation of SVPWM. Fig.6. shows the space vector of three-phase voltage source inverter (VSI) divided into six sectors based on the six fundamental vectors V_x(x=1, 2, 3…, 6).Any voltage vectors in this vector space can be synthesized by two fundamental vectors V_x and V_{x+1}.For example the voltage vector in sector I can be represented as a combination of active vectors $V_1$and V_2.Within a switching cycle T_s, the components for each fundamental vector V_x is related to the occupied time T_n and unoccupied time of the null vectors. The locus of the maximum V_s is represented by the envelope of the hexagon formed by the basic space vectors. Thus the magnitude of V_s must be limited to the shortest radius of this envelope when $V_s$is revolving, which gives a maximum magnitude of $\frac{V_{dc}}{\sqrt{2}}$ forV_s.

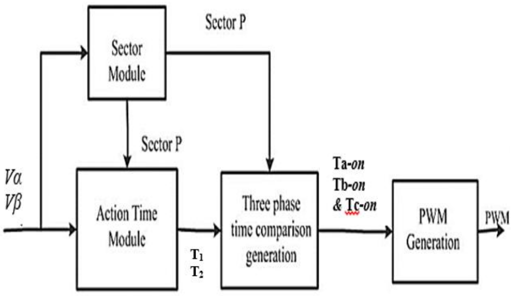

Fig.3. *Block Diagram of SVPWM*

For the computation of sector and vectors, the three phase a-b-c voltage is transformed to *α-β*reference frame using the Clarke Transformations. In Field oriented control of PMSM the *α-β*voltages are obtained from the *d-q*voltages.

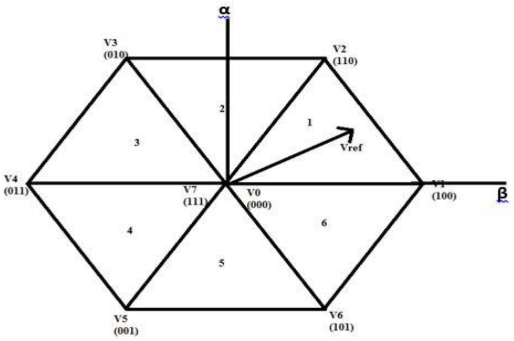

Fig.4. *Sectors of SVPWM*

3.1 Sector Identification

To determine the switching time instants and switching sequence, it is important to know the sector in which the reference vector lies. Following algorithm can be used to determine the sector of the reference output voltage vector. Three intermediate variables are considered asV_{ref1}, V_{ref2} andV_{ref3}. [10]

$$V_{ref1} = V_\beta \text{...}(14)$$

$$V_{ref2} = \frac{\sqrt{3}}{2}V_\alpha - \frac{1}{2}V_\beta \text{................................}(15)$$

$$V_{ref3} = -\frac{\sqrt{3}}{2}V_\alpha - \frac{1}{2}V_\beta \text{..............................}(16)$$

A, B and C are considered as logical variables which takes the values 0 or 1 depending on the conditions:

If V_{ref1}>0, A=1 else A=0…………………………. (17)

If V_{ref2}>0, B=1 else B=0…………………………. (18)

If V_{ref3}>0, C=1 else C=0………………………….. (19)

Using the logical variables A, B and C, the variable N is identified as:

N=A+2B+4C……………………………………….. (20)

Values of N is used to map the sector (P) where, the vector lies using the Table 1.

TABLE 1. *MAPPING OF N TO P*

N	3	1	5	4	6	2
P	1	2	3	4	5	6

3.2 Calculation of Action Time T1 and T2 of Basic Voltage Vector

The action time of two adjacent basic vector in a certain sector is defined as $t_1$and t_2. In traditional SVPWM algorithm, space angles and trigonometric functions are used to calculate the values of $t_1$and t_2, which makes the process complex. In this method these values are calculated using the V_α and V_β. Applying the volt-second balance principle to the orthogonal decomposition rates of the basic vectors, $t_1$and $t_2$can be mapped from Table 2.

Where; X, Y and Z are given by:

$$X = \frac{\sqrt{3}V_\beta T_s}{V_{dc}} \text{...}(21)$$

$$Y = \left(\frac{3}{2}V_\alpha + \frac{\sqrt{3}}{2}V_\beta\right)\frac{T_s}{2V_{dc}} \text{...........................}(22)$$

$$Z = \left(-\frac{3}{2}V_\alpha + \frac{\sqrt{3}}{2}V_\beta\right)\frac{T_s}{2V_{dc}} \text{..........................}(23)$$

Table 2. *Mapping X, Y,Z To T_1 And T_2*

sector	1	2	3	4	5	6
T_1	-Z	Y	X	Z	-Y	-X
T_2	X	Z	-Y	-X	-Z	Y

3.3 Determination of Ta, Tb and Tc:

T_a, T_b and T_c correspond to the time comparison values of each phase. Intermediate variables Ta-on,T*b*-on and T*c*-on are used to map the comparison values from Table 3:

Table 3. *Operationof T_a,$T_b$and T_c*

N	3	1	5	4	6	2
Ta	Ta-*on*	Tb-*on*	Tc-*on*	Tc-*on*	Tb-*on*	Ta-*on*
Tb	Tb-*on*	Ta-*on*	Ta-*on*	Tb-on	Tc-*on*	Tc-*on*
Tc	Tc-*on*	Tc-*on*	Tb-*on*	Ta-*on*	Ta-*on*	Tb-*on*

4. FIELD ORIENTED CONTROL (FOC) OF PMSM

The overall block schematic of FOC of PMSM is shown in Fig. 4.In this control system, stator currents ia&ib are measured using electric current sensors, and i_c is calculated with the formula $i_c=-(i_a+i_b)$. The electric currents i_a, $i_b$and $i_c$are transformed into the direct component i_q, i_d in the revolving coordinate system through the Clarke and the Park transformations. Theni_q, $i_d$can be used as the negative feedback quantity of the electric current loop. The deviation between the given speed and the feedback speed ω* is regulated through the speed PI regulator. The output is q axis reference component i_q*- torque component, which is used to control the torque .The deviations between i_q*, i_d* and current feedback quantity i_q,i_d is fed to the current PI regulators, and the respective output phase voltage V_q* and V_d* on the *d-q* revolving coordinate system. V_q* and V_d* are transformed into the stator phase voltage vector component V_α and V_β under α-β coordinate system through inverse Park transformation. If the stator phase voltage vector V_α, V_β and its sector number is known, the voltage space vector PWM technique can be used to produce PWM signal to control the inverter, so as to achieve closed-loop control of the

PMSM. In the algorithm, i_d*=0 as there is no excitation in the rotor part for a PMSM. This paper presents the simulation of Field oriented control of a surface mounted PMSM using the novel SVPWM

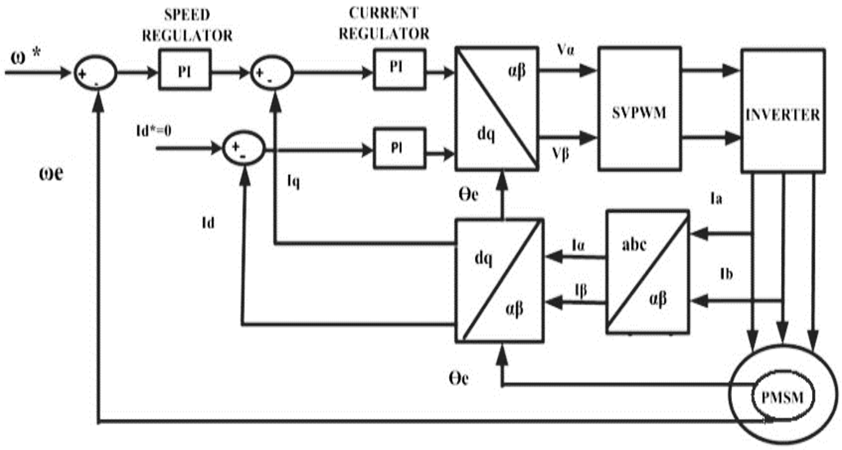

Fig.5. *FOC of PMSM Drive*

5. SIMULATION AND RESULTS AND DISCUSSIONS

Field oriented control (FOC) block diagram scheme has been shown in the fig. 5. Fig.5 also shows the proportional-integral (PI) controller which is used for speed as well as current control loop. Outer loop is speed control loop and the inner control loop is current control loop. For voltage source inverter used the IGBT switches has been used. Direct voltage is generated by diode bridge rectifier with 220*v* 50 H_z3- phase ac source. Simulation is carried out for 10 second. Load torque applied is 8 N-m. Simulation circuit diagram of proposed methodology is shown in fig.6.

5.1 Parameter of PMSM

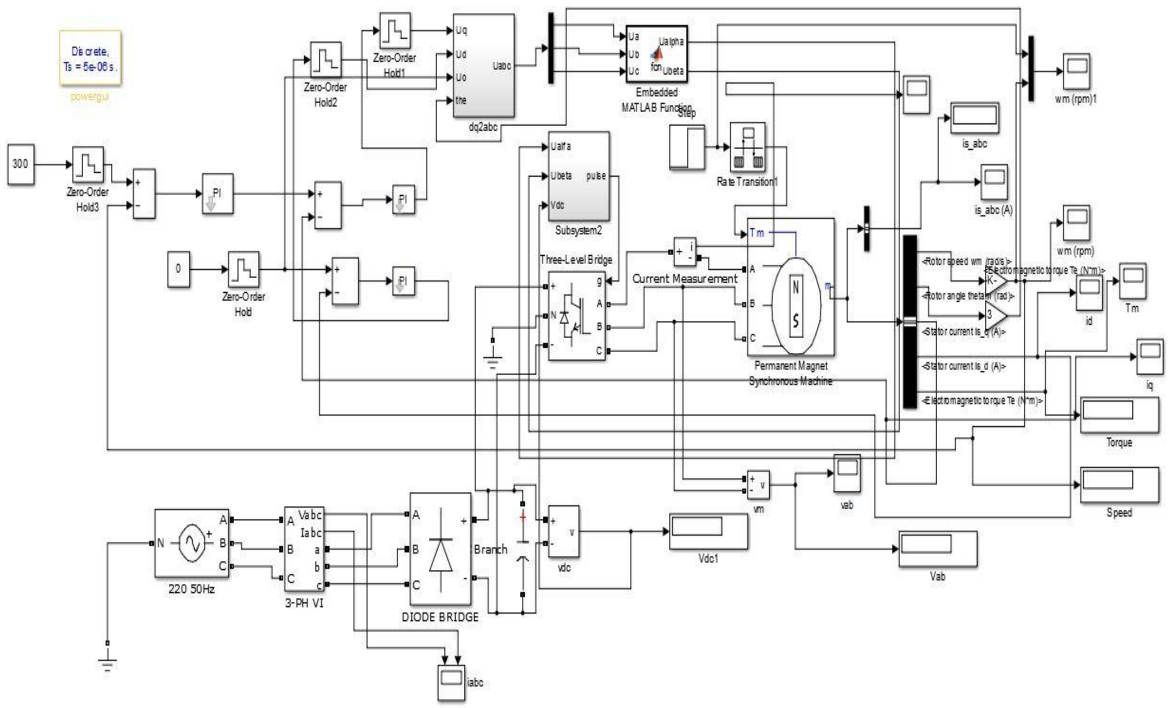

Fig.7. *Simulation Diagram of SVPWM Inverter Fed PMSM Drive*

Permanent magnet synchronous motor parameters are given in table 5.

Table 5. *Parameter of PMSM*

Name of parameter	Value
Number of Pole Pair *p*	4
Stator Resistance	0.9585Ω

Stator Inductance	0.00835H
Flux Linkage	0.01827 v.s
Inertia	0.0046329 kg.m^2
Viscous Damping	0.0003035N.m.s
Rotor Type	Round Rotor

Fig.7 shows the electromagnetic torque of the Permanent magnet synchronous drive. The torque value is stabilize after 0.011sec.

Torque

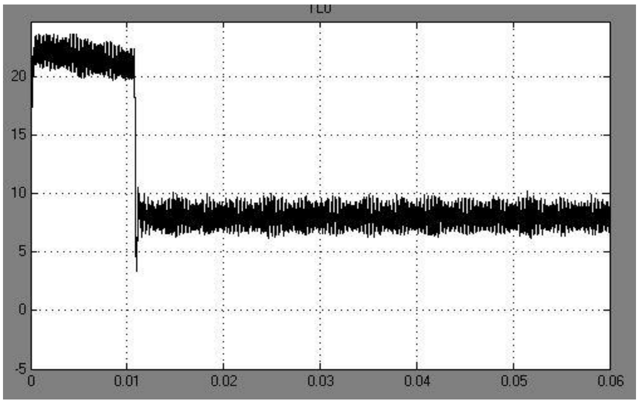

Fig.7. *Electromagnetic Torque*

Fig.8 shows the speed response of PMSM motor based on SVPWM technique which is used as aninverter fed drive for a reference speed of 300 *rpm*. No overshoot have been observed. It may be clearly observed that steady state tracking accuracy is high for proposed controller. PMSM drive gave speed range from 0-300 rpm in 0-0.011 sec and then it stabilize at 300 rpm.

Speed in *rpm*

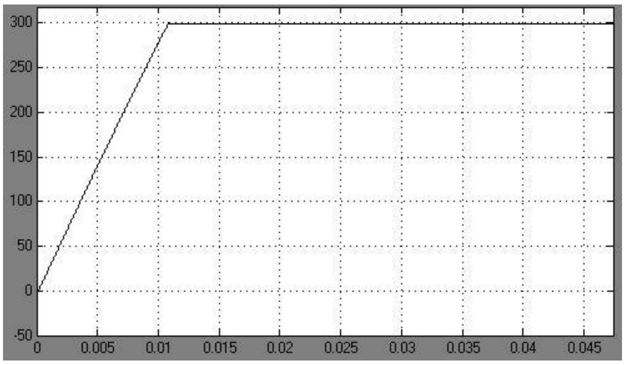

Fig.8. *Speed Response*

Fig.9 shows the stator *d*-*q* voltage.Stator *d*-*q* voltage time axis is shown in mili-second.

Stator Voltage

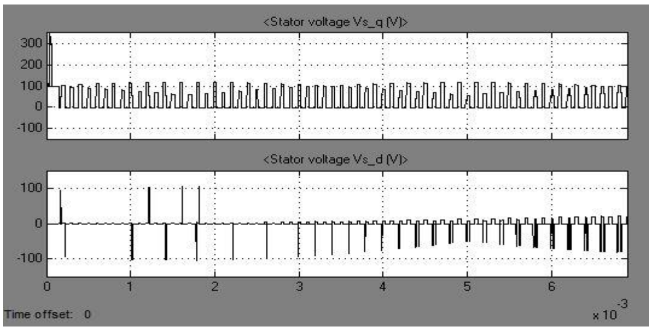

Fig.9. *d-q Axis Voltage*

Fig.10-fig11 shows the stator current of permanent magnet synchronous motor drive. Fig.10is showing the *d*-axis current and fig.11 shows the stator 3-phase a-b-ccurrent.

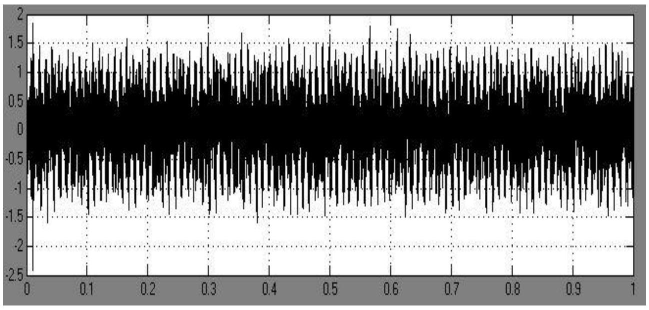

Fig.10. *Stator i_dCurrent*

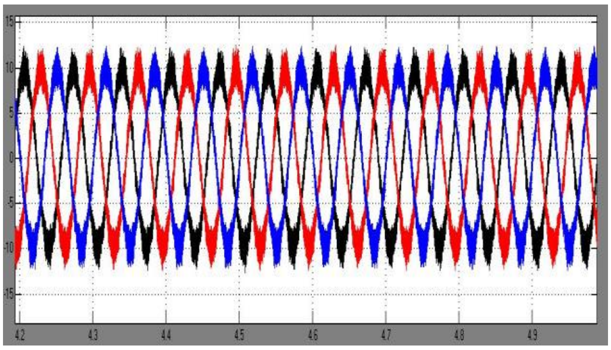

Fig.11. *Stator Current abc*

The input voltage *Vab* of permanent magnet synchronous motor has been shown in fig.12. It is the output voltage of the SVPWM inverter. The SVPWM inverter voltage source is 3- *phase* rectified DC voltage.

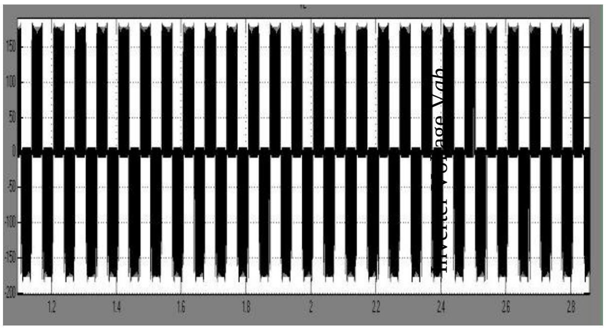

Fig.12. *SVPWMInverter Voltage V_{ab}*

The simulation result with SVPWM method are shown in fig.13. The speed and torque characteristics with respect to time axis has been shown. The speed torque characteristic shows no transient for a PMSM and a smooth operation may be observed after 0.011 sec.

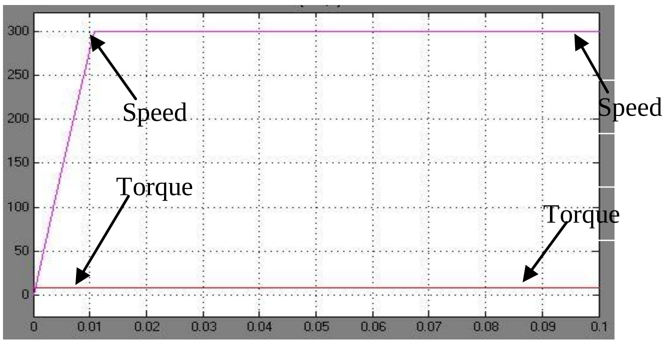

Fig.13. *SpeedandMotor Torque*

6. CONCLUSIONS

This paper present field oriented control (FOC) with space vector pulse width modulation (SVPWM) algorithm for permanent magnet synchronous machine (PMSM). The configuration for the proposed system is designed and simulated using latest MATLAB/Simulink. The paper investigate that the use of SVPWM may provide proper switching state of inverter and optimized the switching patterns. The simulation results shows the reduced torque repels and reduced the speed transients, speed is settled at 0.011 sec. SVPWM controller makes the system robust as there is no overshoot present in speed. Simulation result shows the quicker and dynamic response of the system. Hence the SVPWM is feasible and more effective for application point of view.

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