IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 14, Issue 2 Ser. I (Mar. – Apr. 2019), PP 58-63
www.iosrjournals.org

Modelling and Simulation of FOC based Permanent Magnet Synchronous Motor Drive using SVPWM Technique

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Abstract:*This paper deals with the vector control of a Permanent Magnet Synchronous motor (PMSM) employingSpace vector Pulse Width Modulation (SVPWM).Many industries uses Permanent Magnet Synchronous Motor (PMSM) due to its smaller size, less weight & low rotor loss compare to induction motor of the same capacity. FOC (Field Oriented Control) is a control procedure to operate the motor that results in fast dynamic response and efficient operation at faster speed changes.It allows for accurate dynamic control of speed and torque using PI Controller. The SVPWM (Space Vector Pulse Width Modulation) is a standard modulation technique that provides pulses to the inverter. The mathematical model of a PMSM is discussed and the system was realized with MATLAB/SIMULINK.*

Keywords: *Permanent Magnet Synchronous Motor (PMSM), Space Vector Pulse Width Modulation (SVPWM), Field Oriented Control (FOC), PI Controller, SIMULINK*

Date of Submission: 10-04-2019 Date of acceptance: 25-04-2019

I. Introduction

Field oriented control (FOC) is a classical approach to control ac machines. FOC uses a coordinate system that aligns with the rotorflux, it is called d-q rotating reference frame. The transformation from the three-phase non-rotating reference frame (abc) to dq reference frame for a PMSM is used in this technique.In this frame, an independent control of the electrical torque andthe magnitude of the d-axis flux is achieved by controlling $i_q$andi_q respectively. When stator inductance of direct and quadrature axis are equal, the torque is only dependent on the i_q(quadrature axis current).The flux is maintained constant by setting i^*_q to 0.The measured stator currents i_d and i_q are subtracted from the reference signals i^*_d,i^*_q producing an error signal for the PI controllers. The PI controller generates output voltage in the rotating reference frame which is given to SVPWM to generate the duty cycles to trigger the voltage source inverter.

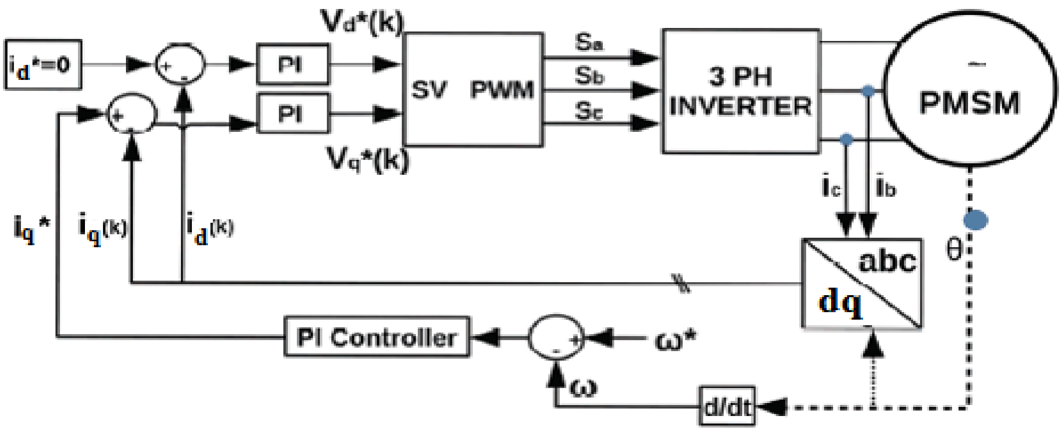

Figure 1:FOC scheme using PI controllers

The outer control loop controls the rotational speed and inner control loop controls the stator current. The outer control loop compare the calculated value of speed and reference rotational speed and gives the error signal to PI Controller which gives the output asi^*_q reference quadrature axis current compon1ent. For current control the measured motor currents must be mathematically transformed from the three-phase static reference frame of the stator windings to the two-axis rotating reference frame by using Park's Transformation. The two new phase variables are denoted by d and q, and are referred to as the motor direct and quadrature axis.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

A. Modelling of PMSM

The voltage equations of PMSM in synchronous rotating frame are as follows:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} + e_d$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + e_q$$

Here,$e_d = -\omega_e L_q i_q$ and $e_q = \omega_e L_d i_d + \omega_e \lambda_d$ (d-axis and q-axis back EMF voltages)

Above equations can be written in matrix form as follows:

$$\frac{d}{dt}\begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d} & \frac{\omega_e(t) L_q}{L_d} \\ -\frac{\omega_e(t) L_d}{L_q} & -\frac{R}{L_q} \end{bmatrix} \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} v_d(t) \\ v_q(t) \end{bmatrix} - \begin{bmatrix} 0 \\ \frac{\omega_e(t) \Lambda_d}{L_q} \end{bmatrix} (1)$$

The electromagnetic torque of motor is given by

$$T_e(t) = \frac{3}{2} \cdot \frac{P}{2} \left[\lambda_d i_q(t) - \lambda_q i_d(t) \right] \quad (2)$$

If d-axis current is set to zero, then Nm per Ampere ratio is maximized. The relation between electromagnetic torque, mechanical load torque and the rotational speed is given by

$$J \cdot \frac{d\omega}{dt} = T_e(t) - T_m - F\omega(t) (3)$$

Table no 1: Electrical and Mechanical specification of the PMSM

Specification of Motor		
R_s	Stator resistance	4.76 Ω
L_{dq}	Stator inductance	0.0268 H
λ_d	Rotor magnetic flux	0.1848 Wb
J	Inertia	0.12 kg.m^2
F	Friction factor	0.015 N.m/s
P	Number of poles	4

B. PI Controller

The error signals are obtained by comparing calculated values and reference values of direct and quadrature axis current components. These error signalsare regulated using a PI controller. The PI controller is defined by the parameters K_p andK_i, representing the proportional and integrating action respectively. The proportional gain is used to amplify the input signal and integrator is used to improve the accuracy of the control system; that is, to minimize the steady-state error.

Table no 2: Control System Parameters

Parameters of Inverter and Controller		
V_{dc}	DC Voltage	48 Volts
fc	Switching frequency	5 kHz
$K_{P\omega}$	Speed P coefficient	1.27
$K_{I\omega}$	Speed I coefficient	0.031
K_{Pi}	Current P coefficient	4.5
K_{Ii}	Current I coefficient	20

By isolating the PI controllers from the time varying currents and voltages, the FOC is able to offer numerous advantages, such as:

- High Efficiency
- Smooth operation at low and high speeds resulting in a wide range of speed
- Fast dynamic response, good transient and steady state performance

C. Three-phase VSI

The IGBT module controls the power flow to the motor. The inverter output line to line voltages according to the switching states S_a, S_b and S_c are as follows:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 0 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{4}$$

The vector S is the switching function with the value 1 when upper leg semiconductor is on and 0 when it is off. Since the two transistors in one inverter leg cannot be turned on at the same time, it will result in eight different switching stages. The IGBTs in three-phase VSI are triggered by SVPWM pulses. Hence, the voltage supply to the machine can be controlled by varying the duty cycle of the triggering pulse.

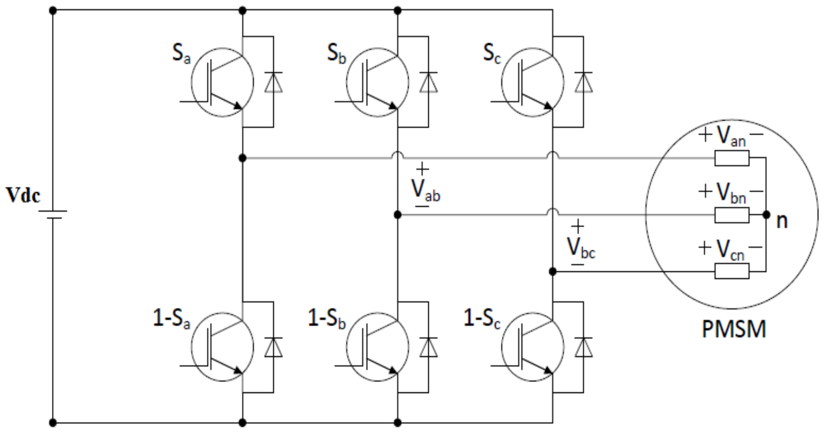

Figure 2: Basic Voltage Source Inverter

D. Space Vector Pulse Width Modulator

Space vector pulse width modulation (SVPWM) is a PWM technique applied in industry for low switching loss, low computational complexity, and high flexibility.

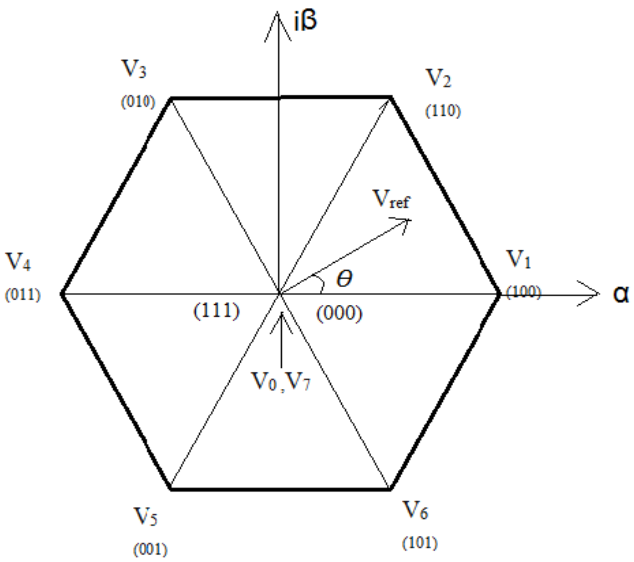

Figure 3: Location of eight possible voltage space vectors for a VSI

The main concept behind Space Vector Pulse Width Modulation is to divide the two dimension plane into six equal areas which are called sectors. The V_1-V_6 are active vectors and other two vectors V_0 and V_7 are called inactive vectors.The basic principle of SVPWM is based on the eight switch combinations of a three-phase inverter. The magnitude of each of the six active vectors is equal to (2/3)V_{dc}. The zero state vectors are used to minimize the switching frequency.

II. Simulation And Results

The simulation for the system response under sudden load torque change and reference speed increment or decrement is carried out. In simulation the sampling time was set equal to 1μs. The parameters of motor, controller and inverter are given in table 1 and 2.

Initially the motor operates at t_0=0 under a load of 4Nm and a step speed command from 0 to 30 rad/s. At t_1=0.5s, load involves a step decrease to 2 Nm. At t_2=1s, the step speed increases to 35 rad/s. Finally, at time t_3=1.5s, the reference speed is decreased by a step command to 15 rad/s.

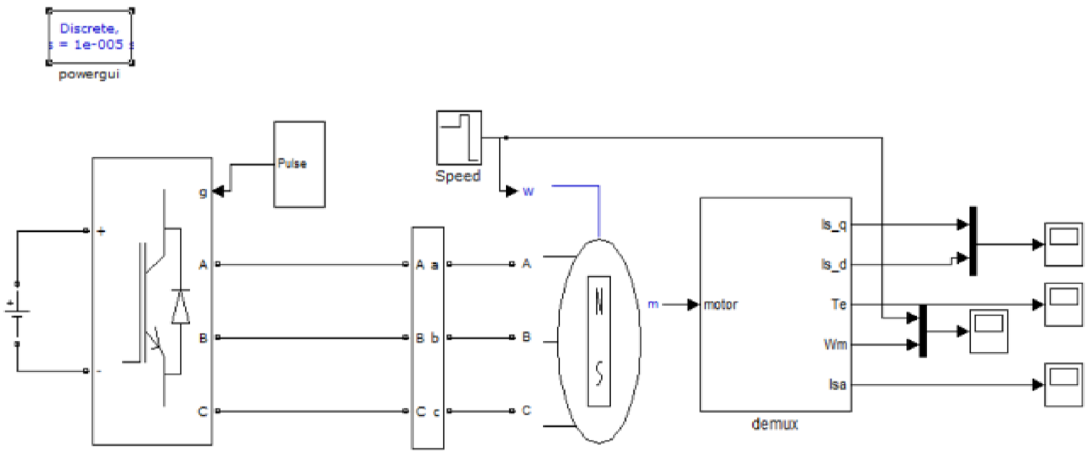

Figure 4: The Simulation Diagram (PMSM field oriented control)

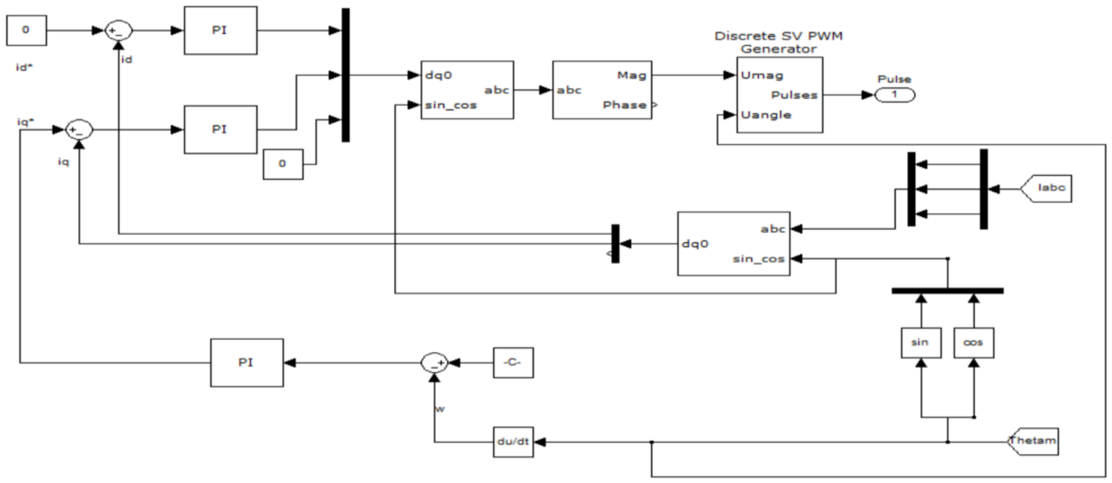

Figure 5: Simulation diagramof pulse triggering

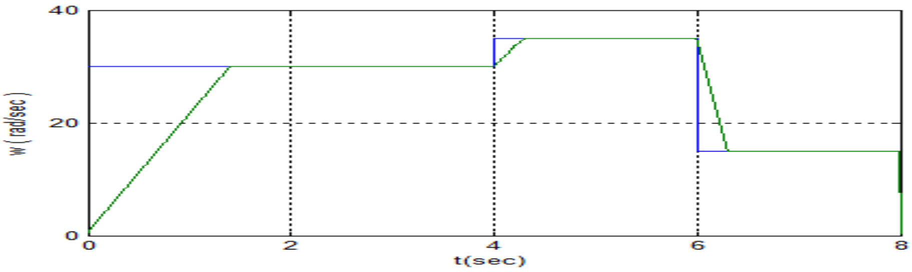

Figure 6: Rotational speed response

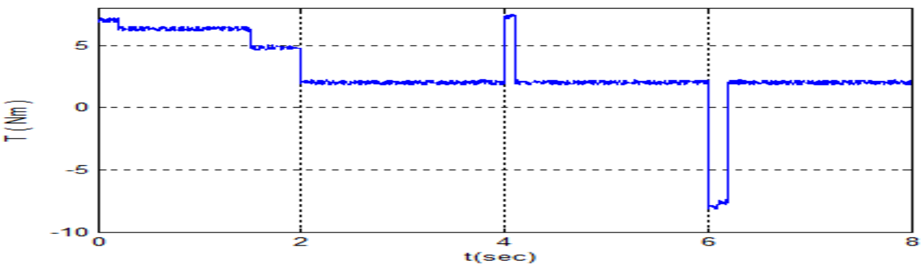

Figure 7: Electromagnetic Torque response

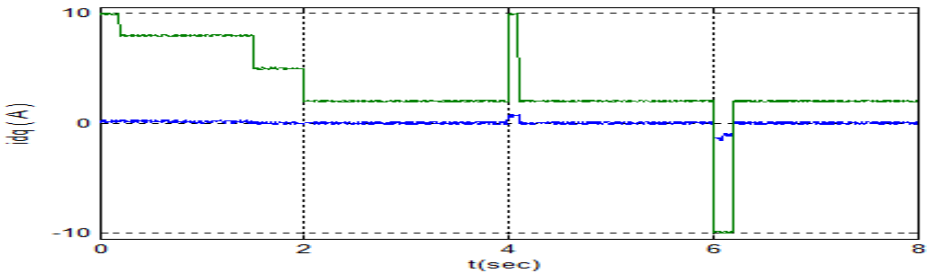

Figure 8: D-Q Current response

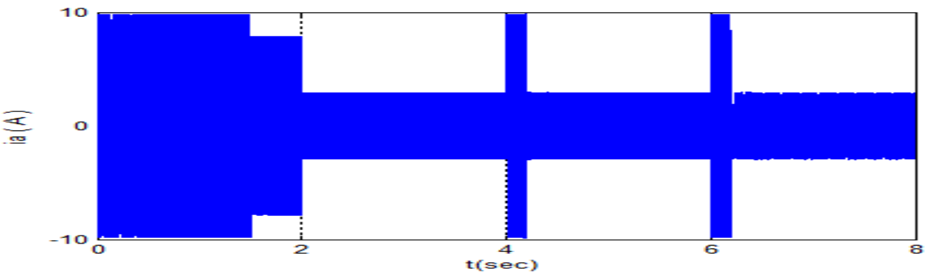

Figure 9: Motor Current $i_a$response

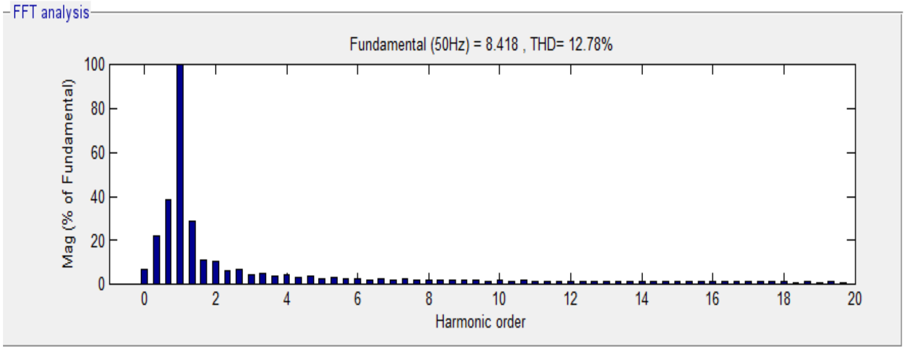

Figure 10:Total Harmonic Distortion(THD) in motor Current

Figure 7 illustrates thatresponse of the electromagnetic torque exhibits low oscillation due to the space vector modulation technique. Figure 8 shows that the current $i_q$is proportional to electromagnetic torque andthe current $i_d$is maintained at zero.

III. Conclusion

TheField Oriented Control (FOC) with SVPWM inverter is simulated using MATLAB/Simulink. The PMSM voltages and rotor angle are sensed to estimate the torque and the stator flux vector to obtainspeed and torque response of PMSM by using SVPWM technique.

The simulation result shows that evenunder the abrupt change in thespeed the steady state of stator current and torque can be achieved. Field Oriented Control ensures fast dynamic response, good transient and steady state performance of motor.Field Oriented Control of a high speed PMSM is suitable for electric vehicle and traction applications.

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Sayali S. Raut"Modelling and Simulation of FOC based Permanent Magnet Synchronous Motor Drive using SVPWM Technique." IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) 14.2 (2019): 58-63.