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MODELLING OF PMSM AND FOC OF PMSM BASED ON SPWM WITH MATLAB/SIMULINK

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ABSTARCT:

Permanent-magnet-synchronous-machine (PMSM) drives have been increasingly applied in a variety of industrial applications which require fast dynamic response and accurate control over wide speed ranges. Permanent magnet (PM) synchronous motors are widely used in low and mid power applications such as computer peripheral equipments, robotics, adjustable speed drives and electric vehicles. The mathematical model of PMSM is analyzed and the system model of FOC vector control has been established. The control system has been also simulated by MATLAB/Simulink.

Keywords: *Permanent-magnet-synchronous-machine (PMSM), Sinusoidal Pulse Width Modulation (SPWM), Field Oriented Control (FOC).*

Abbreviations:

Table 1 Abbreviations

B	friction	L_s	equivalent self inductance
i_d	d-axis current	R_s	stator resistance
i_q	q-axis current	T_e	develop torque
J	inertia	T_L	load torque
L_d	d-axis self inductance	λ_d	flux linkage d axis
L_{ls}	stator leakage inductance	λ_f	PM flux linkage
L_d	d-axis mag. inductance	λ_q	flux linkage due q axis
L_q	q-axis mag. inductance	ω_m	rotor speed
L_q	q-axis self inductance	ω_r	electrical speed

1. INTRODUCTION TO PMSM MOTOR

Electrical ac machines have been playing an important role in industry progress during the last few decades. With the advances in power semiconductor devices, converter topologies, microprocessors, application specific ICs (ASIC) and computer-aided design techniques since 1980s, ac drives are currently making tremendous impact in the area of variable speed motor control systems. Among the ac drives, permanent magnet synchronous machine (PMSM) drives have been increasingly applied in a wide variety of industrial applications due to high power density and efficiency, high torque to inertia ratio, and high reliability. This has opened up new possibilities for large-scale application of PMSM. Consequently, a continuous increase in the use of PMSM drives will surely be witnessed in the near future.

1.1. *Permanent Magnet Synchronous Motor Drive System*

The motor drive consists of four main components, the PM motor, inverter, control unit and the position sensor. The components are connected as shown in Fig. 1.

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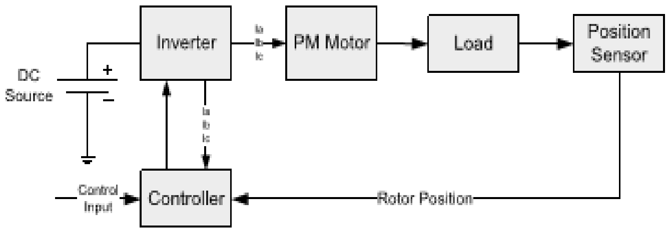

Figure 1 Drive system schematic

Permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. Operation of permanent magnet synchronous motors requires position sensors in the rotor shaft when operated without damper winding. There are four main devices for the measurement of position, the potentiometer, linear variable differential transformer, optical encoder and resolvers. The motor is fed form a voltage source inverter with current control. The control is performed by regulating the flow of current through the stator of the motor.

1.2. *Detailed Modeling of PMSM*

The d-q model has been developed on rotor reference frame as shown in Fig. 2. At any time t, the rotating rotor d-axis makes and angle θr with the fixed stator phase axis and rotating stator mmf makes an angle α with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor [Sebastian *et al* (1986)].

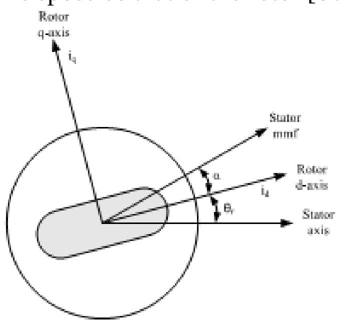

Figure 2 Axis representation of Motor

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions [Sebastian *et al* (1986), Wang X *et al* (2009)]:

1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Eddy currents and hysteresis losses are negligible.
4) There are no field current dynamics.

Voltage equations are given by:

$$V_d = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \qquad (1)$$

$$V_q = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \qquad (2)$$

Flux Linkages are given by

$$\lambda_q = L_q i_q \qquad (3)$$

$$\lambda_d = L_d i_d + \lambda_f \qquad (4)$$

Substituting Eq. (3) and (4) into Eq. (1) and (2),

$$V_d = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho L_q i_q \qquad (5)$$

$$V_q = R_s i_d - \omega_r L_q i_q + \rho(L_d i_d + \lambda_f) \tag{6}$$

Arranging Eq. (5) and Eq. (6) in matrix form,

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \tag{7}$$

The developed torque motor is being given by,

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda_d i_q - \lambda_q i_d\right) \tag{8}$$

The mechanical Torque equation is,

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

Solving for the rotor mechanical speed form Eq. (9),

$$\omega_m = \int \frac{T_e - T_L - B\omega_m}{J}\, dt \tag{10}$$

And

$$\omega_m = \omega_r \left(\frac{2}{P}\right) \tag{11}$$

In the above equations ω_r is the rotor electrical speed where as ω_m is the rotor mechanical speed.

1.2.1. *Parks Transformation and Dynamic d-q Modeling*

The dynamic d q modeling is used for the study of motor during transient and steady state. It is done by converting the three phase voltages and currents to dqo variables by using Parks transformation [Macbahi H. *et al*, (2000)]. Converting the phase voltages variables V_{abc} to V_{dqo} variables in rotor reference frame the following equations are obtained

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{12}$$

Convert V_{dqo} to V_{abc}

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \tag{13}$$

1.2.2. *Equivalent Circuit of Permanent Magnet Synchronous Motor*

Equivalent circuits of the motors are used for study and simulation of motors. From the d-q modeling of the

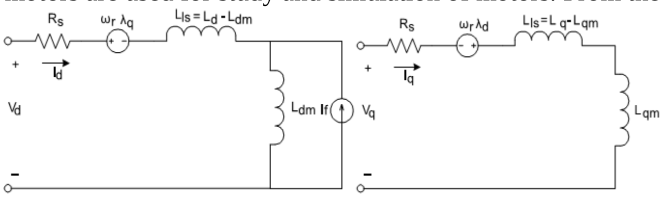

Figure 3 PMSM electric circuit

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motor using the stator voltage equations the equivalent circuit of the motor can be derived. Assuming rotor d axis flux from the permanent magnets is represented by a constant current source as described in the following equation $\lambda_f = L_{dm}i_f$, and Fig. 3 is obtained.

1.3. *PM Motor Control*

Control of PM motors is performed using field oriented control for the operation of synchronous motor as a dc motor [Wang X *et al* (2009)]. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor as shown in Fig. 4

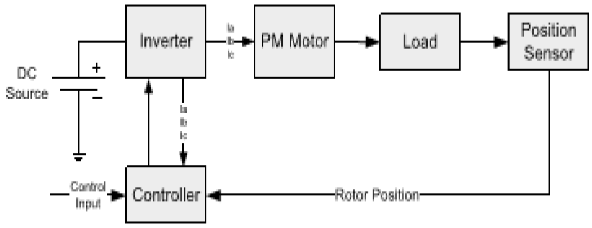

Figure 4 Drive system schematic.

Some control options are constant torque and flux weakening. These options are based in the physical limitation of the motor and the inverter. The limit is established by the rated speed of the motor, at which speed the constant torque operation finishes and the flux weakening starts as shown in Fig. 5.

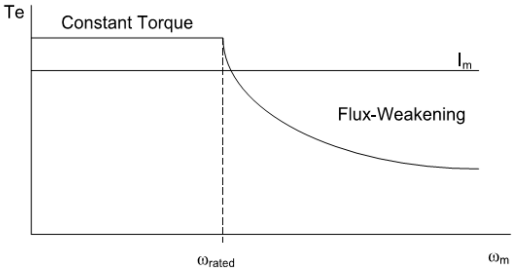

Figure 5 Torque-speed characteristic in steady state

1.3.1. *Field Oriented Control of PM Motors*

Field oriented control was invented in the beginning of 1970s and it demonstrates that an induction motor or synchronous motor could be controlled like a separately excited dc motor by the orientation of the stator mmf or current vector in relation to the rotor flux to achieve a desired objective. In order for the motor to behave like DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of permanent magnet motor. This needs a resolver or an absolute optical encoder. Knowing the position, the three phase currents can be calculated. Its calculation using the current matrix depends on the control desired.

The PMSM control is equivalent to that of the dc motor by a decoupling control known as field oriented control or vector control. The vector control separates the torque component of current and flux channels in the motor through its stator excitation. The vector control of the PM synchronous motor is derived from its dynamic model [Wang X *et al* (2009)].

Considering the currents as inputs, the three currents are:

$$i_a = I_m sin(\omega_r t + \alpha) \tag{14}$$

$$i_b = I_m sin\left(\omega_r t + \alpha - \frac{2\pi}{3}\right) \tag{15}$$

$$i_c = I_m sin\left(\omega_r t + \alpha + \frac{2\pi}{3}\right) \tag{16}$$

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Where α is the angle between the rotor field and stator current phasor, ω_r is the electrical rotor speed.

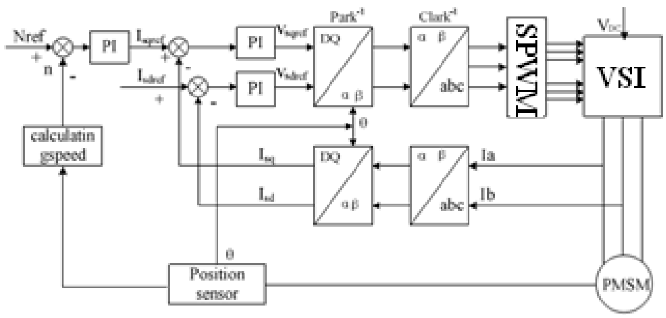

Figure 6 Block diagram of field oriented vector control system for PMSM

The block diagram of field oriented vector control system is shown below. The previous currents obtained are the stator currents that must be transformed to the rotor reference frame with the rotor speed ωr, using Park's transformation [XU Jun-Feng *et al*, (2005)]. The q and d axis currents are constants in the rotor reference frames since α is a constant for a given load torque. As these constants, they are similar to the armature and field currents in the separately excited dc machine. The q axis current is distinctly equivalent to the armature current of the dc machine; the d axis current is field current, but not in its entirety. It is only a partial field current; the other part is contributed by the equivalent current source representing the permanent magnet field. I_d and i_q in terms of I_m as follows

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = I_m \begin{bmatrix} sin\alpha \\ cos\alpha \end{bmatrix} \tag{17}$$

Using Eq. (1), (2), (8) and (17) the electromagnetic torque equation is obtained as given below.

$$T_e = \frac{3}{2}\frac{P}{2}\left[\frac{1}{2}(L_d - L_q)I_m^2 sin2\alpha + \lambda_f I_m sin\alpha\right] \tag{18}$$

1.3.2. *Constant torque operation*

This is performed by making the torque producing current iq equal to the supply current Im. That results in selecting the α angle to be 90 º degrees according to Eq. (17). By making the id current equal to zero the torque equation can be rewritten as [Song K., Liu W., (2008)]:

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_f i_q \tag{19}$$

This indicates that like the dc motor, the torque is dependent of the motor current.

2. THE ESTABLISHMENT OF THE FOC SIMULATION MODEL

Mathematical model of permanent magnet motor has been developed using Eq. (1) to (19). Simulation has been

Table 2 PMSM parameters

Ld	0.0066
Lq	0.0058
Rs	1.4
P	6
B	0.00038818
J	0.001760
λ_f	0.1546

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carried out for vector control in which field oriented control strategy is selected for motor. Table 2 shows parameters of PMSM motor for which simulation is carried out [Bose B. K., (2002)].

2.1. *MATLAB Model*

After analyzing the mathematical model of PMSM and the principle of field-oriented vector control system, the simulation model of field-oriented control system is established. The simulation model is under the environment of MATLAB7.0/Simulink using, due to its rich module libraries [Ong C.-m., (1998), Macbahi H. *et al*, (2000)].

The system structure is shown as figure 7, and the main simulation modules are introduced as follows:

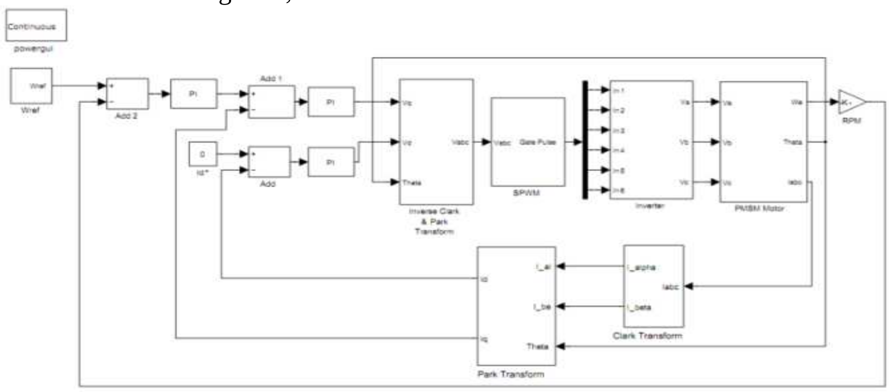

Figure 7 FOC system simulation diagram based on SPWM

2.1.1. *PMSM Motor Modeling:*

By using Eq. (1) to (13), we can develop the PMSM motor model in MATLAB/ Simulink as shown in figure.

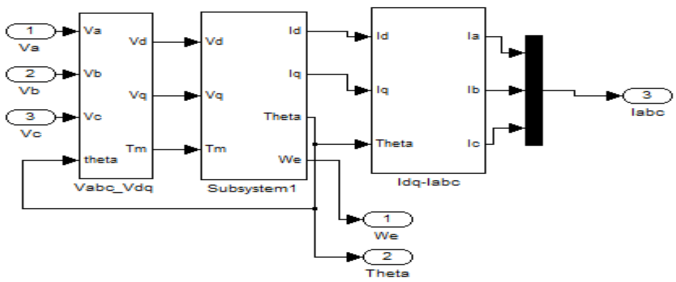

Figure 8 Mathematical model of PMSM

2.1.2. *SPWM:*

In this design the Sinusoidal Pulse Width Modulation (SPWM) technique has been used for controlling the inverter as it can be directly controlled the inverter output voltage and output frequency according to the sine functions. SPWM techniques are characterized by constant amplitude pulses with different duty cycles for each period. In SPWM technique three sine waves and a high frequency triangular carrier wave are used to generate PWM signal. Generally, three sinusoidal waves are used for three phase inverter. The sinusoidal waves are called reference signal and they have 120 phase difference with each other. The frequency of these sinusoidal waves is chosen based on the required inverter output frequency (50 Hz). The carrier triangular wave is usually a high frequency (in several KHz) wave. The switching signal is generated by comparing the sinusoidal waves with the triangular wave. The comparator gives out a pulse when sine voltage is greater than the triangular voltage and this pulse is used to trigger the respective inverter switches. Conventional SPWM signal generation technique in MATLAB/Simulink environment for three phase voltage source inverter is shown in Fig. 9.

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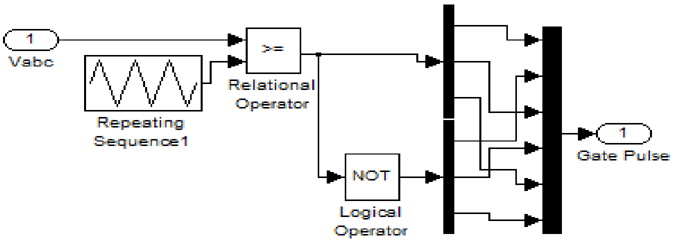

Figure 9Simulink structure of SPWM

3. SIMULATION RESULT

Simulation has been carried out in MATLAB/ Simulink environment by two different operating conditions. First with change in reference speed with constant load torque and second one is change in load torque by keeping the speed of motor being constant.

CASE 1:

In this case the entire model is working on fix load torque of 1 Nm and initially the motor is being run at 100 RPM in first two second as shown in Fig. 10 (a). At t=2 sec the reference speed is suddenly changed and increased to 150 RPM as shown in Fig. 10 (a) and again at t=4 sec it again decreased to 100RPM and at t=5 sec it increased to 200 RPM as shown in Fig. 10 (a). the response of the motor speed is shown in Fig. 10 (b).

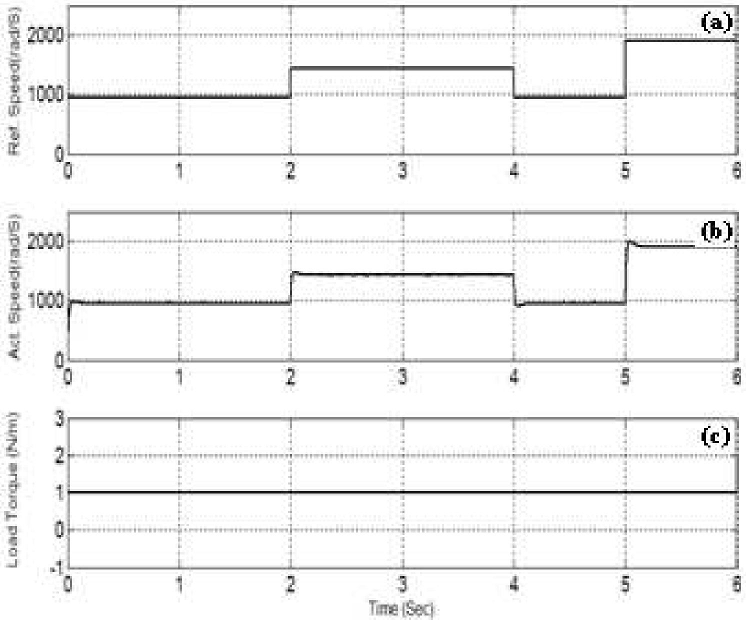

Figure 10 Simulation result for constant load and change in speed

From that we can say that actual speed of the motor is also follow the reference speed and it takes few second to achieve the reference speed. The whole operation is carried out on constant load torque of 1 Nm as shown in Fig. 10 (c).

CASE 2:

In this case the entire model is working with fix constant speed and change in load torque. According to theory the speed should not be changed while change in load and that condition is achieved in this case and that we can analyze with the following simulation result. Initially the motor is run at 200 RPM and 1 Nm load torque. At time t= 6 sec the load is changed from 1 Nm to 2 Nm as shown in Fig. 11 (c).

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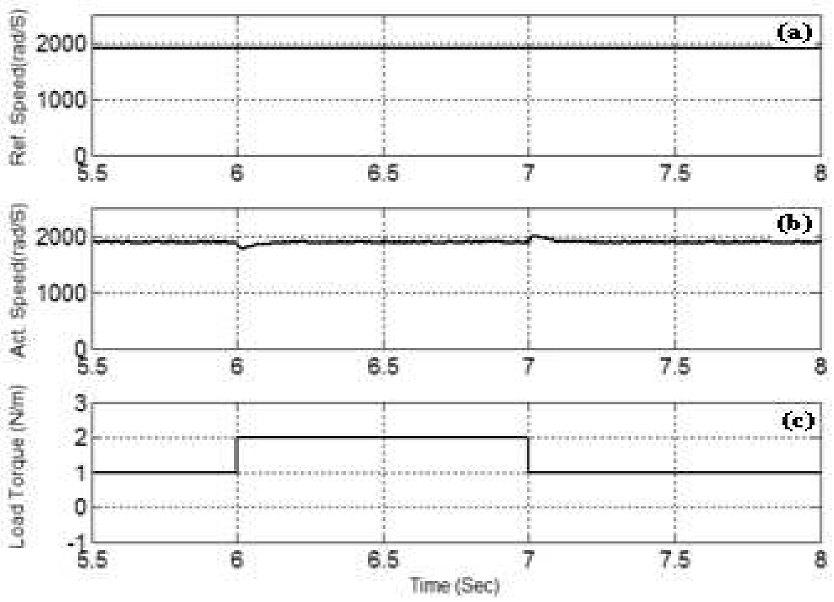

Figure 11 Simulation result for constant speed and change in load

During this period the actual speed of the motor just deviate from its reference for few second and again achieve its reference on increased load. again at time t=7 second the load torque is reduced to 1 Nm again and the motor achieve its reference speed of 200 RPM after deviating a little bit due to change in load.

4. CONCLUSION

In this paper mathematical modeling of PMSM is carried out using MATLAB. Switching sequence of inverter is generated by sinusoidal pulse width modulation. Field oriented vector control is quite precise and gives the precise control to the motor speed. By FOC we can run the motor synchronously at any sudden load change.

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