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Analysis of Permanent Magnet Synchronous Motor under Different Operating Condition Using Vector Controlled in MATLAB

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Abstract: This paper presents the modeling of Permanent Magnet Synchronous Motor and its application with Vector Control technique under different operating condition such shaping, cutting, grinding or shearing require constant torque, irrespective of speed. Other application in cranes and conveyors handling constant weight of material per unit time, in pumps, screw conveyors, compressors and ball mills, for traction drive. Simulation results shows that proposed system has high acceleration and retardation rate with vector control overall fast dynamic response as well as good controlling ability.

Keywords: Permanent magnet synchronous motor; Vector Control; current control loop; speed control loop; Constant torque; Traction; Electrical vehicle.

P	number of poles of the motor
i_a, i_b, i_c	a, b, and c phase currents (in amperes)
i_d, i_q	d and q axis currents (in amperes)
e_a, e_b, e_c	a, b, and c phase back emfs (in volts)
v_a, v_b, v_c	a, b, and c phase voltages (in volts)
v_d, v_q	d, q axis voltages (in volts)
v_{dc}	dc bus voltage (in volts)
J	moment of inertia, kg-m^2
L_a, L_b, L_c	self inductance of a, b, and c phases (in henrys)
L_{ab}	mutual inductance between a, and b Phase (in henrys)
L_d, L_q	d, q axis inductance (in henrys)
λ_{af}	mutual flux due to magnet (in Webers)
λ_d, λ_q	d, q axis flux linkages (in webers)
p	derivative operator d/dt
R_s	stator resistance
L_s	average inductance $L_s = (L_q+L_d)/2$
L_x	inductance fluctuation $L_x = (L_q-L_d)/2$
λ_m	flux linkage due to permanent magnet
θ_r	electrical angle between a-axis and q-axis in Degrees
ω_s	synchronous speed (in rad/sec)
ω_r	$\omega_r = p\theta$, angular velocity of rotation (In electrical rad/sec)
T_e	electromagnetic torque in (N-M)
$T_{l:}$	Load Torque in (N-M)
α and β	stationary frame α-axis and β-axis.
B	viscous friction coefficient (N/rad/sec)

I. INTRODUCTION

Now a day's permanent magnet synchronous motor drives, which include permanent magnet synchronous motor (PMSM) and brushless dc motor (BDCM) could become a close competitors to induction motor drives for servo applications. [1]-[3]. The PMSM has a sinusoidal back emf and requires sinusoidal stator current to produce constant torque. The PMSM is very similar to the standard wound rotor synchronous machine except that the PMSM has no damper windings and excitation is provided by the permanent magnet instead of a field winding. The PMSM are widely used in low and medium power applications such as computer peripheral equipments, robotics, adjustable speed drives, electric vehicles and constant torque application in various industries like steel mills and in transportation for material handling. [2], [3]

Selection of traction machines for electric vehicle is important and needs to get enough attention [5], [6]. The major requirements of electric vehicles are high instant power and high power density, high torque at low speed and a high power at high speed, wide speed range, fast torque response, high efficiency over the wide speed and torque ranges, high efficiency for regenerative breaking, reliability and robustness, Reasonable cost.

The growth in the market of PM motor drives has demanded the need of simulation tools 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. [1]

The general classification of PM machine is radial flux (drum-type) and axial flux (disc-type), and the former type is more commonly used. A sinusoidal machine can be a surface permanent magnet (SPM) or an interior type or buried permanent magnet (IPM) type. In SPM, PMs are glued on the rotor surface using epoxy adhesive. Unlike in

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an interior PM the magnets are mounted inside the rotor [9], [12].

This paper analyzes the mathematical modeling, simulation of PMSM in MATLAB environment using vector control under different operating conditions such as i) step rise in load ii) step change in reference speed iii) speed reversal, and simulation for electric vehicle load.

The paper is arranged as follows:

Section II presents the mathematical model of the PMSM. Section III scalar and vector control. Section IV. Different types of load. Section V. Electric vehicle load, VI. Drive System. VII. Simulation Results. VIII. AC6 PMSM Synchronous Motor Drive system. Section IX has the Conclusion.

II. MATHAMATICAL MODEL OF THE PMSM

The stator of the PMSM and the wound rotor synchronous motor are similar. In addition there is no difference between the back emf produced by permanent magnet and that produced by an excited coil. Hence the mathematical model of a PMSM is similar to that of the wound rotor synchronous motor. The following assumptions are made in derivation. [1]- [4]

Assumptions

- Stator winding produces distribution mmf. Space harmonics in the air gaps are neglected.
- Air gap reluctance has a constant component as well as sinusoidal varying component.
- Balanced three phase supply voltage is considered. Although magnetic saturation is considered, eddy current and hysteresis effects are neglected.
- Damper windings are not considered.

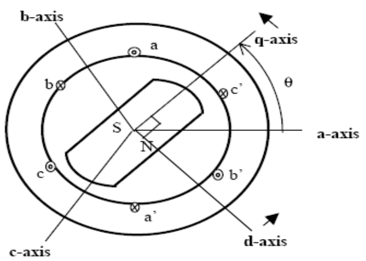


Fig 2.1.PM Synchronous Motor

With these assumptions the stator d, q equation in the rotor reference frame of the PMSM are [2], [3]

$$v_d = R_s i_d + p\lambda_d - \omega_r \lambda_q \quad (1)$$

$$v_q = R_s i_q + p\lambda_q - \omega_r \lambda_d \quad (2)$$

where

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

and

$$\lambda_d = L_d i_d + \lambda_{af} \quad (4)$$

λ_{af} is the magnet mutual flux linkage

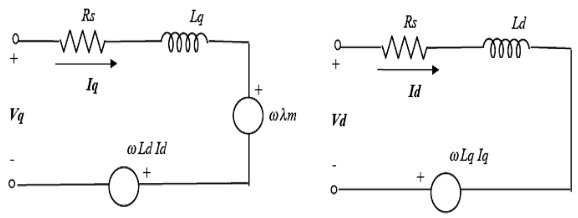
The input power p_i is represented as

$$p_i = v_a i_a + v_b i_b + v_c i_c \quad (5)$$

While in terms of d, q variables

$$Power = 3(v_d i_d + v_q i_q)/2 \quad (6)$$

Equivalent Circuit of a PM Synchronous Motor



(a) q-axis circuit (b) d-axis circuit

Fig 2.2.Equivalent Circuit of a PM Synchronous Motor

Fig.2.2 shows the dynamic equivalent circuit of IPM synchronous machine. Note that in practice, magnetic circuits are subjected to saturation as current is increases. Especially, when i_q is increased, the value of L_q is decreased and L_m and L_d are subjected to armature reaction. Since id is maintained to zero or negative value (demagnetizing) in most operating conditions, saturation of L_d is rarely occurs.[2], [3], [4]

The electric torque Te produced by motor

$$T_e = 3P\,[\,\lambda_m i_q + (L_d - L_q)\, i_d i_q\,]/2 \quad (7)$$

Equation for the motor dynamics

$$T = T_l + B\omega_r + Jp\omega_r \quad (8)$$

It is from equation (7) that the produced torque is composed of two distinct mechanisms. The first term correspond to “the mutual reaction torque” occurring between i_q and the permanent magnet. While the second term correspond to “the reluctance torque ” due to the differences in d-axis and q-axis reluctance or (inductance) For constant flux operation when i_d equals zero, the electric torque T_e

$$T_e = 3\lambda_m i_q/2 = k_t i_q \quad (9)$$

Where k_t is the motor torque constant. This torque equation is resembles that of the regular dc machine and hence provides ease of control. [2]-[3]

Park’s Transformation

v_d and v_q are obtained from v_a, v_b, and v_c through park’s transformation as given below[2-6]

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$$\begin{bmatrix} vq \\ vd \\ vo \end{bmatrix} = 2/3 \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} va \\ vb \\ vc \end{bmatrix} \quad (10)$$

Here v_o component is called the zero sequence components and under balanced three phase system this component is always zero. Since it is a linear transformation a, b, c variables are obtained from d, q variables through the inverse of the park's transformation as given below.

$$\begin{bmatrix} va \\ vb \\ vc \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} vd \\ vq \\ vo \end{bmatrix} \quad (11)$$

Where θ is the rotor position

Note that in order to produce additive reluctance torque, i_d must be negative since $L_d > L_q$

III. SCALAR AND VECTOR CONTROL

In scalar control the magnitude of variables is control and scalar control is simple to implement. Inherent coupling effect (Both torque and flux are the functions of voltage or current and frequency) gives the sluggish response and the system is easily prone to instability because of a high order fifth system effect, i.e. If torque is increased by increasing the slip (frequency), the flux tend to decrease and flux variation is always sluggish. For controlling the flux additional voltage is required (Boost voltage).This temporary dipping of flux reduces the torque sensitivity with slip and increases the time response. This problem is solved by using the vector control or FOC. [7-12]

In FOC, both the magnitude and phase alignment of vector variables are control. Vector control drive operates like a separately excited D.C. motor drive because of D.C. machine-like performance and vector control is known as decoupling or orthogonal control. Vector control is applicable to both induction and synchronous motor drives. [8], [12]

D.C. Drive Analogy

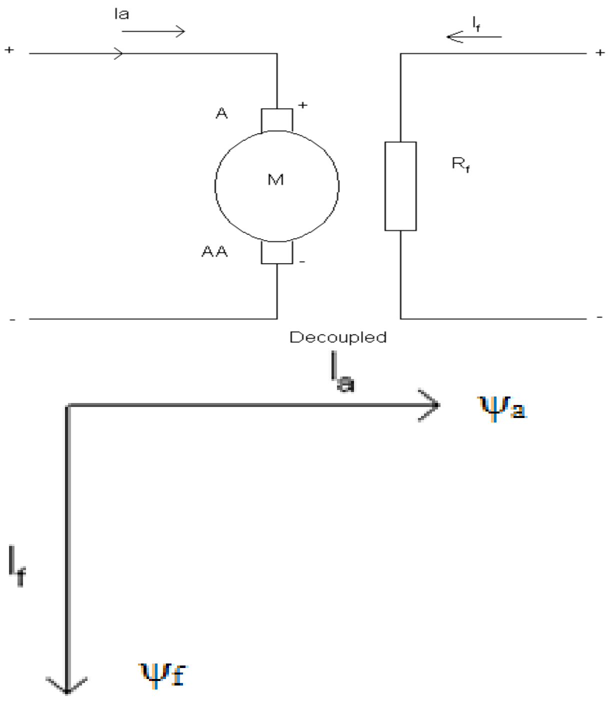

Fig.3.1. Separately Excited DC Motor

In separately excited DC machine both torque and field component is orthogonal and hence independently control. The electric torque equation of a separately excited DC machine as given below

$$T_e = K_t \psi_f \psi_a = K_t I_a I_f \quad (12)$$

Where k_t = motor torque constant, i_a =Torque component (armature current), i_f = Field component (field current)

Vector Control of PMSM

This vector control strategy is somewhat similar to that of PM synchronous motor vector control, except, in vector control of PMSM for maximum torque sensitivity with the stator current, we can set $i_d = 0$ and $i_a = i_{qs}$. The slip frequency $\omega_{sl} = 0$ because the machine always runs at synchronous speed ω_e. The magnetizing current $i_{ds} = 0$ because the rotor flux is supplied by permanent magnet [8], [12]. This condition is also gives a minimal inverter power rating. Equation (3) and (4) can be represented in phasor diagram as given below in fig.3.2.

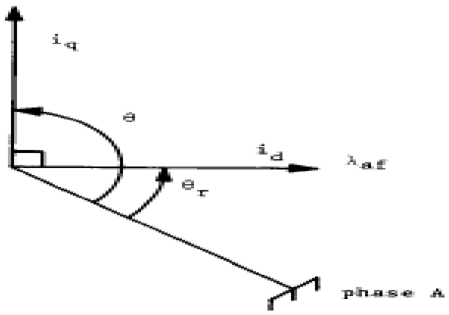

Fig.3.2. phasor diagram of vector controller

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IV. DIFFERENT TYPES OF LOAD

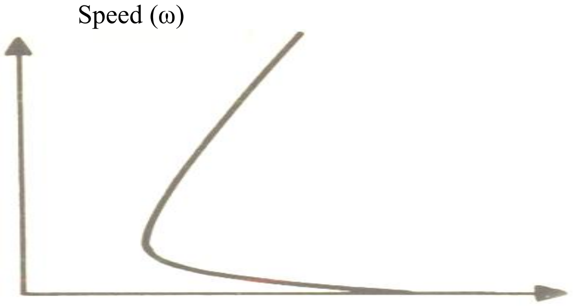
Different type of loads exhibit different speed-torque characteristics. [16],[18] However, most of the industrial loads can be classified into the following categories

- Constant type load torque Most of the working machines that have mechanical nature of work like shaping, cutting, grinding or shearing, require constant torque irrespective of speed. Similarly cranes during the hoisting and conveyors handling constant weight of material per unit time also exhibit this type of characteristics.
  Typical examples of constant torque applications include, Conveyors, Extruders, Mixers, Lift machines, Positive displacement pumps and compressors
- Torque proportional to square of the speed (Fan type load) Another type of load met in practice is the one in which load torque is proportional to the square of the speed. E.g. fans, rotary pumps, compressors and ship propellers.
- Torque inversely proportional to speed (Constant power type load)

This type of load sometimes found in the industry. The power remains constant while the torque varies. The torque is inversely proportional to the speed, which infinite at zero speed and zero torque at infinite speed. In practice, there is always a finite value to break away torque required. This type of load is characteristic of the traction drives, which require high torque at low speed for the initial acceleration, then a much reduced torque when at running speed.

V. ELECTRIC VEHICLE LOAD

Speed (ω)



Load Torque (Tl)

Fig4.5.speed-torque curve for electric vehicle

Fig4.5 shows the speed-torque characteristics of an electric vehicle load. Because of its heavy mass, the stiction is large near zero speed; net torque is mainly due to stiction. The stiction disappeared at a finite speed and then windage and viscous friction dominant. Because of large stiction and need for accelerating a heavy mass, the motor torque required for starting a electric vehicle is much larger than required to run it at full speed.

VI. DRIVE SYSTEM

The drive system consists of permanent magnet synchronous machine, speed and position feedback, a PWM inverter and signal builder for loading. A 3-phase motor rated 1.1kw, 220V, and 3000 rpm is fed by PWM inverter [12], [13], [15]. Its output voltage goes through controlled source block before being applied to the PMSM stator windings.

The load torque applied to the machine shaft is build with the help of signal builder from MATLAB library. Using signal builder we can construct different types of load torque curve. Two control loops are used. The inner loop regulates the motor currents called current control loop. The outer loop controls the motor speed called as speed control loop. In this id=0 methodology is used [1], [2].

VII. SIMULATION RESULTS

Simulation model of PMSM using id=0 control method to control the speed and d-q axis current, with PI control. According to vector control of PMSM, the model runs in MATLAB.

At starting the torque increases transiently from standstill. During the start up period, the speed is also increase linearly due to vector control so the commanded torque is equal to the maximum capability of the motor. This ensures that machine runs up in shortest time possible. Fig.8 (a), 8(b), 8(c) shows the different operating condition of PMSM using vector control methodology in Matlab.

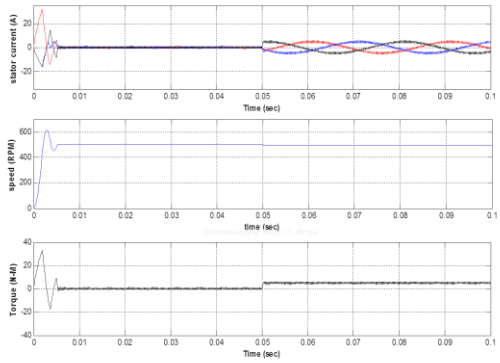


Fig 8 (a).Step rise in load

We can see that the current and torque response time is very short and very small fluctuation in speed. We can see that the during steady state operation the speed is constant and current maintain a good sinusoidal waveform shown in fig 8(a). From figure 8(a): at the time of starting motor is running at no load with zero load torque so it is called as no load operation but at t=0.05 sec step changed in load from no load to a torque of 6 N-M.the torque is very high but the same time motor achieve the reference speed due to vector control. The system runs very smoothly.

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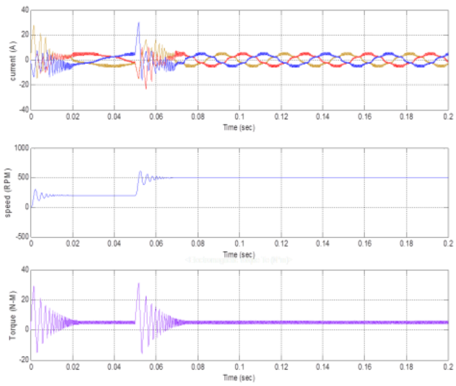

Fig 8(b). Step change in reference speed

From simulation result we can see that speed can be change from reference speed to desired speed by changing the frequency of supply. The reference speed is 200 rpm after 0.05 sec the supply frequency is changed so as to achieve the 500 rpm and from figure 8(b): current is sinusoidal and speed response is very smooth. From simulation result we can see that speed can be change from reference speed to desired speed by changing the frequency of supply. The reference speed is 200 rpm after 0.05 sec the supply frequency is changed so as to achieve the 500 rpm and from figure 8(b): current is sinusoidal and speed response is very smooth.

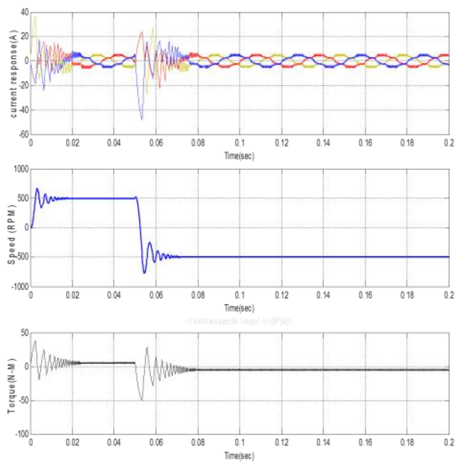

Fig 8 (c).Speed Reversal

From figure 8 (c) the speed reversal of PMSM is possible by changing the phase sequence of the supply system, from R-Y-B to Y-R-B.

At starting reference speed is 500 rpm but at 0.05 sec speed becomes -500 rpm. At the same time the phase sequence of supply is also change as shown in current waveform.

Fig.8 (d), Simulation results show that system has high acceleration and retardation and from fig.8 (c), speed reversal is also possible which is desired characteristics for EVs, machine can run smoothly and has good static as well as dynamic performance which is more efficient for traction application (Electric Vehicle).In each operating condition current and torque response time is very short and very small fluctuation in speed. We can see that the during steady state operation the speed is constant and current maintain a good sinusoidal waveform.

VIII. AC6 - PM SYNCHRONOUS MOTOR DRIVE

The PM synchronous motor is fed by a PWM voltage source inverter, which is built using a Universal Bridge Block. The speed control loop uses a PI regulator to produce the flux and torque references for the vector control block. The vector control block computes the three reference motor line currents corresponding to the flux and torque references and then feeds the motor with these currents using a three-phase current regulator. Motor current, speed, and torque signals are available at the output of the block.

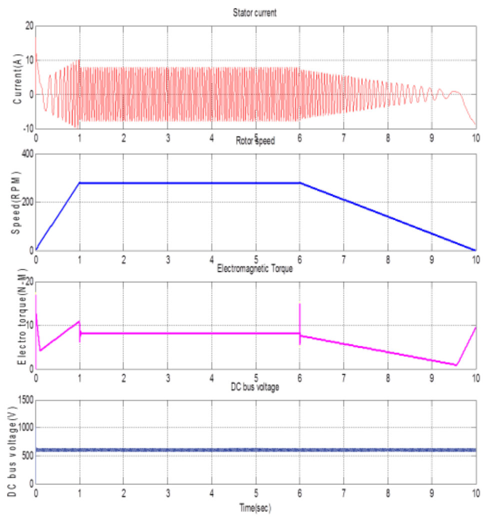

Fig.9 (a) Simulation result for electric vehicle load

From figure 9 (a) it is observed can the motor stator current, the rotor speed, the electromagnetic torque and the DC bus voltage on the scope. The speed set point and the torque set point are also shown.

At starting t=0 set speed is 300 rpm, it is observed that speed followed precisely the acceleration ramp it is called as acceleration

At t = 1 sec, the full load torque is applied to the motor. We can observe a small disturbance in the motor speed, which stabilizes very quickly.

At t = 6 sec, the speed set point is changed to 0 rpm. The speed decreases down to 0 rpm following precisely the deceleration ramp. This period is called as retardation. From this result we can say that system exhibit speed-torque curve for electric vehicle hence this drive system is suitable for electric vehicle application.

IX. CONCLUSION

This paper has presented modeling, simulation, and analysis of a vector-controlled PMSM drive under

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different operating condition and suitable for traction application. Since vector control transform the PMSM to an equivalent separately excited dc motor. The result indicates that the small and large signal responses are very similar. The large and small signal speed response is same. Simulation results show that system has high acceleration and retardation and it can run smoothly and has good static as well as dynamic performance which is more efficient for traction application (Electric Vehicle).

The vector control is a good methodology for analysis and design of PMSM drive system. It provides designing and debugging for practical drive system.

Finally we concluded that Modeling and different types of Permanent Magnet Synchronous Motor is studied and Simulation is carried in Matlab and performance is studied at different operating conditions. It is found that PMSM motor can be used for variety of application under different operating condition due to high power, high torque, and High acceleration and deceleration rates.

APPENDIX

We have the following motor parameters

Power = 1.1 KW

R_a = 2.875 ohm

Φ = 0.175 w_b

L_d = 0.0085H

L_q = 0.0085H

J = 0.008 kg-m^2

Pole Pair = 2

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