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PMSM Mathematical Model Comparison with Simulink Model

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Abstract

Presence of permanent magnets in its rotor assembly the power density of permanent magnet synchronous motor is higher than one of induction motor with the same ratings due to no stator power is dedicated to the magnetic field production. PMSM has more advantages like compact form with high torque density and less weight, higher continuous torque over a wider range of speeds, lower rotor inertia, higher dynamic performance under load, higher operational efficiencies with no magnetizing current, and the corresponding absence of heat due to current in the rotor, low torque ripple effect, more robust performance compared to dc motors, because of these advantages Permanent magnet synchronous motors are increasing applied in several areas such as traction, automobiles, robotics and aerospace technology. In this paper mathematical modelling of PMSM is done and simulation results compared with MATLAB SIMULINK model.

Keywords : permanent magnets, high torque density, mathematical modelling, torque ripple, two axis model

Introduction

With introduction of permanent magnets to replace the electromagnetic poles with windings requiring an electric energy supply source resulted in compact dc machines. Likewise in synchronous machines, the conventional electromagnetic field poles in the rotor are replaced by the PM poles and by doing so the slip rings and brush assembly are dispensed. With the advent of switching power transistor and silicon-controlled rectifier devices the replacement of the mechanical commutator with an electronic commutator in the form of an inverter was achieved. These two developments contributed to the development of PMSMs and brushless dc machines. The armature of the dc machine need not be on the rotor if the mechanical commutator is replaced by its electronic version. Therefore, the armature of the machine can be on the stator enabling better cooling and allowing higher voltages to be achieved as significant clearance space is available for insulation in the stator. The excitation field that used to be on the stator is transferred to the rotor with the PM poles. Based on arrangement of permanent magnets on the rotor there are many types of PMSMs like surface-mounted PMSM, surface-inset PMSM, interior PMSM, Line-start PMSM.The permanent magnet motors classified based on type of back emf induced. Permanent magnet synchronous motor has sinusoidal back emf and Brushless DC motors have trapezoidal back emf. The silent features of PMSM motor are:

- Due to low inertia used in servo applications.
- High torque density.
- High reliability (no brush wear), even at very high achievable speeds.
- High efficiency.
- Low EMI.

Modelling of PMSM

The dynamic model of the permanent magnet synchronous machine is derived using a two-phase motor in direct and quadrature axes. This approach is done to obtain conceptual simplicity of modelling. The rotor has no windings, only magnets. The magnets are modelled as a current source or a flux linkage source, concentrating all its flux linkages along only one axis. Constant inductance for windings is obtained by a transformation to the rotor by replacing the stator windings with a fictitious set of d-q windings rotating at the electrical speed of the rotor. The equivalence between the three-phase machine and its model using a set of two-phase windings is derived and this approach is suitable for extending it to model an *n* phase machine where *n* is greater than 2, with a two-phase machine. The transformation from the two-phase to the three-phase variables of voltages, currents, or flux linkages is derived. From the obtained current and flux linkages electromagnetic torque is derived. The differential equations describing the PMSM are nonlinear.

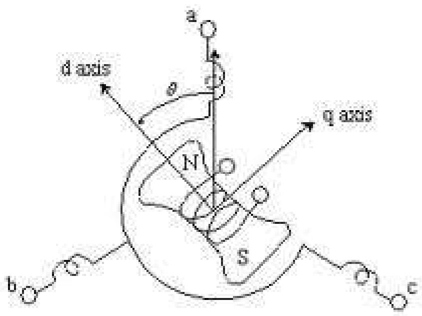

Fig1. A two-phase PMSM

The windings d,q axis are displaced in space by 90 electrical degrees and the rotor winding is at an angle θr from the stator d-axis winding. It is assumed that the q-axis leads the d-axis to a counter clockwise direction of rotation of the rotor. A pair of poles is assumed for this figure, but it is applicable with slight modification for any number of pairs of poles. Note that θr is the electrical rotor position at any instant obtained by multiplying the mechanical rotor position by pairs of electrical poles. The d- and q-axes stator voltages are derived as the sum of the resistive voltage drops and the derivative of the flux linkages in the respective windings as

$V_{qs} = R_s i_{qs} + i_{qs}pL_{qq} + L_{qq}pi_{qs} + L_{qd}pi_{ds} + i_{ds}\ p\ L_{qd} + \lambda_{af}p\sin\theta_r$ (i)

$V_{ds} = R_s\ i_{ds} + i_{qs}pL_{qd} + L_q dpi_{qs} + L_{dd}pi_{ds} + i_{ds}\ p\ L_{dd} + \lambda_{af}p\cos\theta_r$ (ii)

where - *p* is the differential operator(d/ d*t*)

V_{qs} and V_{ds} are the voltages in the q- and d-axes windings

i_{qs} and i_{ds} are the q- and d-axes stator currents

R_q and R_d are the stator q- and d-axes resistances

λ_{qs} and λ_{ds} are the stator q- and d-axes stator flux linkages

L_{qq} and L_{dd} are the self-inductances of the q- and d-axes windings

θ_r is the instantaneous rotor position

The rotor type is surface mounted in which the inductances are equal, the self inductances and mutual inductance of windings is found, and rearranging the terms the motor equations are obtained I stator reference as

$$\begin{bmatrix} Vqs \\ Vds \end{bmatrix} = R_s \begin{bmatrix} iqs \\ ids \end{bmatrix} + \begin{bmatrix} L1 & 0 \\ 0 & L2 \end{bmatrix} d/dt \begin{bmatrix} iqs \\ ids \end{bmatrix} + \lambda_{af} w_r \begin{bmatrix} cos\theta r \\ -sin\theta r \end{bmatrix} \quad \text{(iii)}$$

The equations reveal that inductances are rotor position dependent,the rotor position dependency is eliminated by transformation.

Transformation To Rotor Reference Frames

The rotor field position determines the induced emf and affects the dynamic system. So by viewing the entire system from the rotor, i.e., rotating reference frames, the system inductance matrix (equ.iii) becomes independent of the rotor position, thus leading to the simplification and compactness of the system equations. Reference frames rotating at the speed of the rotor is referred to as rotor reference frames. The relationship between the stationary reference frames denoted by ds and qsaxes and the rotor reference frames denoted by d^r and q^raxes. Transformation to obtain constant inductances is achieved by replacing the actual stator and its windings with a fictitious stator having windings on the q_r and d_r –axes. The fictitious stator will have the same number of turns for each phase as the actual stator phase windings and should produce the equivalent mmf. The actual stator mmf in any axis (say q or d) is the product the number of turns and current in the respective axis winding. The mmf produced by the fictitious stator windings on the q- and d-axes is same as actual stator mmf. Similarly, the same procedure is repeated for the d-axis of the actual stator winding. This leads to a cancellation of the number of turns on both sides of the q- and d-axes stator mmf equations, resulting in a relationship between the actual and fictitious stator currents. The relationship between the currents in the stationary reference frames and the rotor reference frames currents is written as.

$$i_q d_s = [T] i^r_q d_s$$

and similarly voltage relation is given as

$$v_q d_s = [T]\ v^r_q d_s$$

Where T is transition matrix

$$T^t = \begin{bmatrix} cos\theta r & sin\theta r \\ -sin\theta r & cos\theta r \end{bmatrix}$$

The PMSM model in rotor reference frames is obtained as

$$\begin{bmatrix} Vrqs \\ Vrds \end{bmatrix} = \begin{bmatrix} Rs + Lqp & wrLd \\ -wrLq & Rs + Ldp \end{bmatrix} \begin{bmatrix} iqs \\ ids \end{bmatrix} + \begin{bmatrix} wr\lambda af \\ 0 \end{bmatrix} \quad \text{(iv)}$$

Where w_r is the rotor speed in electrical radians per second.

The equations that are derived is for a two-phase PMSM but PMSMs withthree phases are prevalent in industrial applications. A dynamic model for the three-phase PMSM is derived from the two phase machine bythe equivalence between the three and two phases is established. The equivalence is based on the equality of the mmf produced in the two-phase and three-phase windings and on equal current magnitudes.Assuming that

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each of the three-phase windings has $T1$ turns per phase, and equal current magnitudes, the two-phase windings will have $3T1/2$ turns per phase for mmf equity. The d- and q-axes mmfs are found by resolving the mmfs of thethree phases along the d- and q-axes. Then three phase to two phase transformation (abc to dq0).

Electromagnetic Torque

The dynamic equations of the PMSM can be written as

$V=[R]\, i+[L]pi+[G]\, w_r i$ (v)

By pre multiplying Equ.(10) by the transpose of the current vector, the instantaneous input power is

$P_i=i^tV=i^t[R]\, i+i^t[L]pi+i^t[G]w_r i$ (vi)

Where

[*R*] matrix consists of resistive elements

[*L*] matrix consists of the coefficients of the derivative operator *p*

[*G*] matrix has elements that are the coefficients of the electrical rotor speed,θ_r

The term $i^t[R]$ I gives stator and rotor resistive losses. The term $i^t[L]$ pi denotes the rate of change of stored magnetic energy. The air gap power, is given by the term $i^t[G]w_r i$. The air gap power is the product of the mechanical rotor speed and air gap or electromagnetic torque. Hence, the air gap torque, T_e, is derived from the terms involving the rotor speed, w_m, in mechanical rad/s, as

$w_m T_e= P_a=i^t[G]\, i\, w_r$

$=i^t[G]i[P/2]w_m$ (vii)

wherePis the number of poles.

Cancelling speed on both sides of the equation leads to an electromagnetic torque that is

$T_e=(P/2)\, i^t[G]\, i$

(viiii)

Substituting [*G*] in Equ.(13) with the observation from Equ.(9), the electromagnetic torque is obtained as

$T_e= (3/2)(P/2)[\lambda_{af}+(L_d-L_q)i^r_{dr}]i^r_{qr}$ (N.m) (ix)

Modeled Equations in Simulink Blocks

Three pahse supply of Vrms =220V, f=50 Hz is provided as source. Using Parks Transformation three phase is transformed into two pahse for ease of modelling. Parks Transformation give Direct axis (d), Quadrature axis(d) and zero-sequence currents. Zero sequence currents are terminated.

A. Current Subsystem:

The stator currents i_q, i_d are derived by state space model and these are represented in the subsystems as shown in the fig 2.

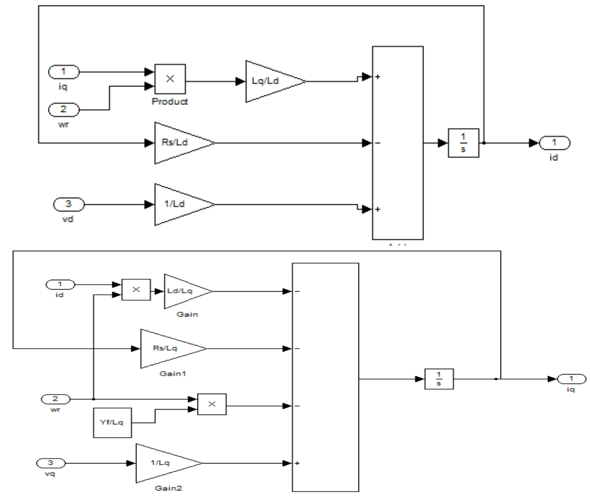


Figure 2. Current equations Block(id,iq)

B. *Torque Sub model :*The electromagnetic equation that is derived equ (14) is implemented in the subsystem as shown in fig 3.

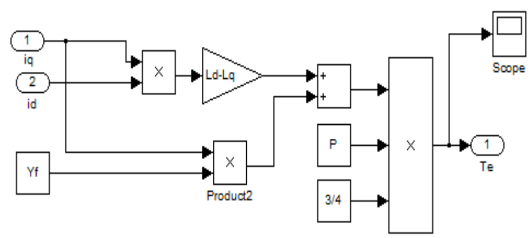


Figure 3.ElectromagneticTorque Block

C. Speed Sub model:

The electromagnetic torque of motor is given by $T_e = Tl + Bw_m + Jpw_m$ (15)

Where B - Friction coefficient,

J – Inertia of motor,

p – Derivative

And from above equation speed (w_m) is found as $w_m = (T_e - T_l - Bw_m)^* 1/J$ (16)

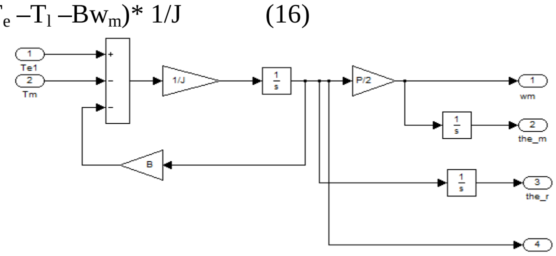


Figure 4. Motor Speed, Rotor Position

The mathematical model of PMSM is compared with MATLAB PMSM model, it is as shown below

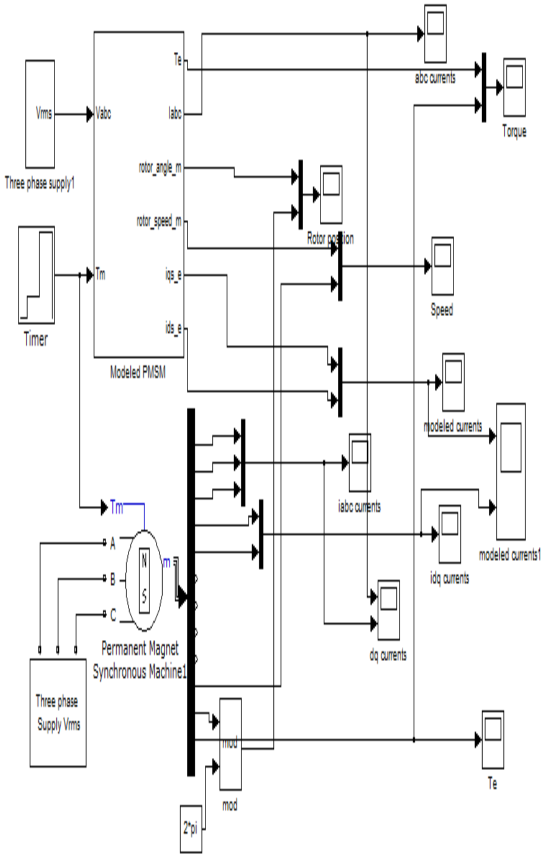
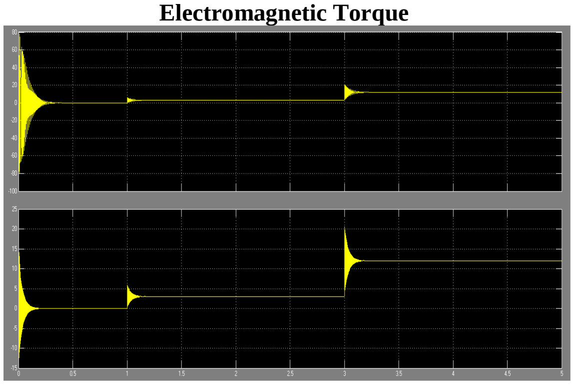


Figure 5.Complete simulation model

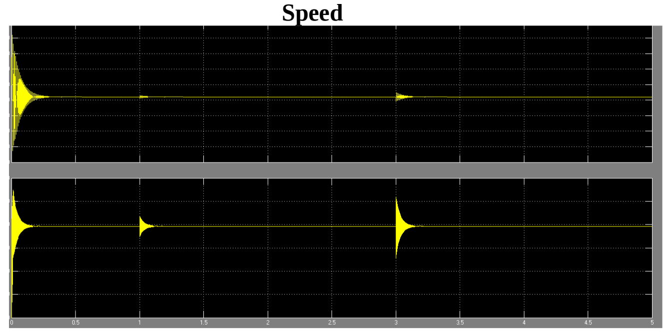
Simulation Result

The motor simulation is carried out for with values Stator Resistance Rs= 1.2Ω
B = 5.12752e-5 kg/m^2
J = 1.235e-5 N-m s
Direct axis Inductance(L_d) = 0.0057 H
Quadrature axis Inductance(L_q) = 0.0125 H
flux – 0.123 V s
Poles=4
Vrms = 230V

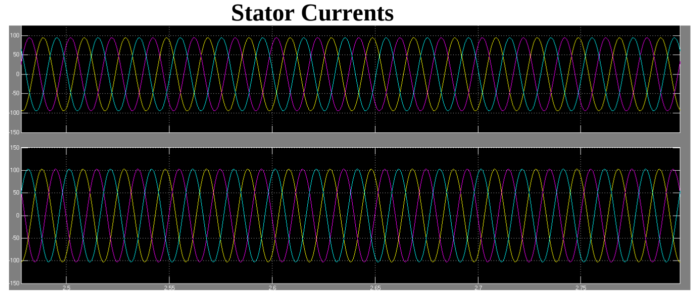
Electromagnetic Torque



Speed



Stator Currents



Rotor Position

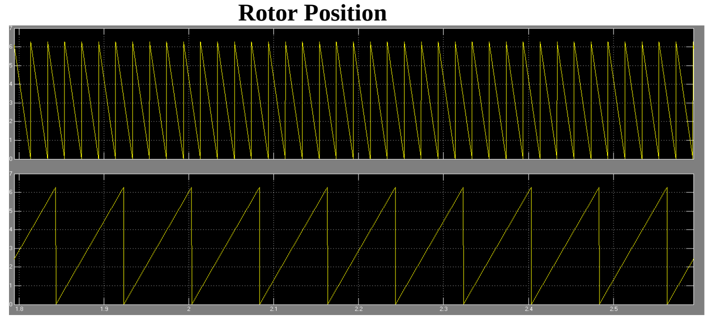


Figure 6. Electromagnetic Torque, Speed, Stator Currents, Rotor position

Conclusion

In this paper simulation based mathematical model of permanent magnet synchronous motor is implemented using MATLAB. The performance characteristics of permanent magnet synchronous motor, i.e. speed of motor, the stator currents and electromagnetic torque magnitudes are obtained and compared with results of MATLAB SIMILINK model Pl PMSM. In extension to the work a suitable drive can be implemented by choosing appropriate drive based on application.

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