Permanent Magnet Motor Rotor Analysis & Performance Analysis

Chiranjib Mukherjee[1] Poulomi Chatterjee[2] Sayantan Dutta[3]
[1,2]Assistant Professor
[1,2,3]Department of Electrical Engineering
[1,2,3]NSHM Knowledge Campus Durgapur, India

Abstract— This paper presents the rotor analysis and the performance analysis of permanent magnet synchronous motor there are quite much rotor configuration available for PMSM application. This paper copes with two usual rotor configuration using the same stator winding. The performance analysis of the motor is done as PMSM motor could become serious competitor to the Induction motor. For low and mid power application such as computer peripheral equipments, robotics, adjustable speed drives, electric vehicles The most important features of PMSM is high power density, high torque per inertia ratio, high operating efficiency. As the loss in PMSM is comparatively low than Induction motor. Mathematic modeling of PMSM is carried out and simulated using MATLAB and the performance of PMSM is compared with Induction motor and the advantage of using PMSM motor is shown in this paper.

Key words: Permanent Magnet Synchronous Motor, High Efficiency, High Power Density, Pronounced Choice, Mathematic Modeling

I. Introduction

Ac motors is very important aspects of electrical field such as Induction motor, synchronous motor. For more efficiency and high performance now days permanent magnet synchronous motor (PMSM) are used keeping the stator winding same permanent magnet rotor is introduce, no requirement of excitation brushes and slip ring, as permanent magnet is used that's why field winding losses get reduce increases the thermal efficiency of the motor.

The recent development in permanent magnet machine has provided a solution of variable speed application, which offers easy design for controller as well as operate at higher efficiency [1][2]

Mainly there are two different rotor configurations. It is quite difficult to find the optimal machine layout for the actual application. First of all the pole number and slot number configuration should be chosen. The pole and slot number combination defines usually the noise and pulsating torque level of the machine [3].PMSM can take the place of Induction motor in industrial application for its better performance.

PMSM also works on very high power factor that's why PMSM is also use for power factor correction process

II. Rotor construction & analysis

There are two principal design of PMSM rotor, i) surface mounted magnet type, ii) interior magnet type, Figure 1 shows the two different design of PMSM

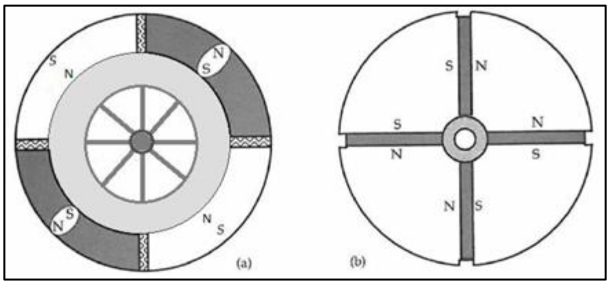

Figure 1 a) Surface Mounted PM, b) Interior Magnet Type PM

As shown in figure 1(a). the magnet is mount on the surface of the rotor, the magnet can be regarded as air because the permeability of the magnets is close to unity and saliency is not present as because the width of the magnet is same, Therefore the direct axis inductance and quadrature axis inductance is same (Ld=Lq).As shown in figure 1 (b) In interior magnet type the magnets are placed inside the rotor, In this configuration saliency is available as a result the air gap between direct axis and quadrature axis air gap is not same , the quadrature axis inductance is greater than that of direct axis inductance (Lq>Ld)

The drawback of a low L_d(–value) is the very short field weakening range, as the armature reaction with a surface magnet construction is very weak. This means that a high demagnetizing stator current component would be required to decrease the air gap flux, and consequently, there would be very little current left on the q-axis to produce the torque [4].

III. Magnetic modeling

Magnetic modeling can be based on the analysis of magnetic flux density and magnetic field strength in different part of the machine. The machine will typically have the same number of flux path as the number of pole, from Ampere's Law the magneto motive (MMF) release to the current linkage.

$$MMF = \oint H.dl=\sum i = Ni = Ø \qquad 1.1$$

In the theory of magnetic modeling, the concept of magnetic circuit the model is used .An analogy to electrical circuit is common where equation (1.2) is analogs to Ohms law [5]

$$U = MMF = ØR \qquad 1.2$$

U represents the magnetic voltage which equals the MMF .R and Ø represents the magnetic reluctance and magnetic flux respectively, the magnetic conductivity, known as presence related to the reluctance, as follows

$$P = 1/Rm = (\mu Sm)/l \qquad 1.3$$

Where Sm is the cross-sectional area of the material, l is the length μ is the permeability.

IV. Magnetic circuit model

In figure 1.1 , shows a small principle part of the permanent magnet including the flux following in rotor and stator back iron is present , this sketch represent three magnetic poles linearly this should be noted that this is a real machine this will follow the curvature of the stator

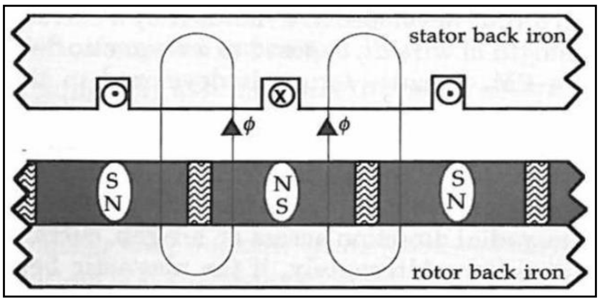

Fig. 1.1: Principal Linear Structure of PMSM Machine Including the Flux Path

The magnetic circuit model of one single flux path of figure (1.1) is shown, In the figure (1.2) the notation of the Ø/2 is used based on the fact that the air gap flux invariably has contribution from two magnets [6].

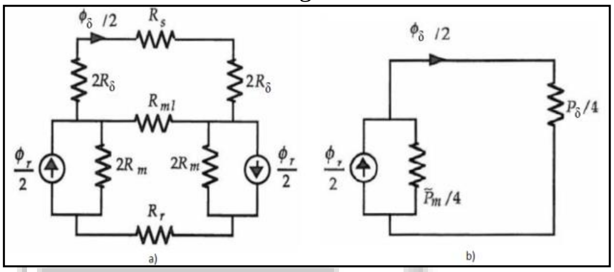

Figure 1.2 (a) Magnetic circuit model, (b) Simplification of circuit model [6]

Analytical model from the circuit model shows in figure (1.2) (b) following expression can be write from the circuit

$$Ø\delta/2= (P\delta/4)/ (P\delta/4+ṔpM/4) \quad ØR/2 \qquad 1.4$$

Which can be simplify to

$$Ø\delta= 1/(1+ṔpM/P\delta) \quad Ør \qquad 1.5$$

Where the combination of magnetic permeance and magnetic leakage permeance can be expressed

$$ṔpM = PpM + 4Pml \qquad 1.6$$

The concentration factor is define as

$$CØ = SpM / S\delta \qquad 1.7$$

Respectively based on the air gap surface area of the permanent magnet

$$SpM = \alpha p\ M\ Tp\ lb \qquad 1.8$$

And the area of air gap

$$S\delta= (Tplb\ (1+ \alpha pM))/2 \qquad 1.9$$

This area is represent the air gap area per pole and approximate an average value, the cross-sectional area where the flux is flowing will increasing at increases in diameter, when approaching the stator

Further the magnetic leakage factor is

$$Kml=1+4hpm/(\pi\mu r\alpha PMTp)\ln(1+\pi\delta/(1-\alpha PM)Tp) \qquad 1.10$$

A low magnetic leakage flux will result in high performance of the machine the closer Kml is to 1 the better the performance.

Performance coefficient is define as

$$Pc= hpM/\delta CØ \qquad 1.11$$

This is essential of calculating flux density as describe in equation (1.12). Finally the relation between the air gap flux density and the remanent flux density can be express as

$$B\delta= CØ/(1+ (\mu rKcKml)/Pc) \quad Br \qquad 1.12$$

V. MATHEMATICAL MODELING OF PMSM

Considering the interior magnetic type rotor, the magnetic modeling of a PMSM can be derive from its d-q model, it can be obtain from the well-known model of Induction machine by removing the damper winding and field current dynamics The synchronously rotating rotor reference frame is chosen so the stator winding quantities are transformed to the synchronously rotating reference frame that is revolving at rotor speed.

The PMSM model without damper winding has been develop in rotor reference frame using following assumptions.

1) Saturation is neglected
2) The induce EMF is sinusoidal
3) Core loss are negligible
4) There are no field current dynamics

It is also been assumed the rotor flux is constant at a given operating point and concentrated along the d axis while there is zero flux along the q axis an assumption similarly made in the derivation of indirect vector control of induction motor drive[7]. The rotor reference frame is chosen because the position of the rotor magnet determines independently of the stator voltage and current, the instantaneous induce emf and subsequently stator current and the torque of the machine. When rotor reference frame is conceder, it means equivalent q and d axis stator winding are transfer to reference frame that are revolving at rotor speed, the consequence is that there is zero speed differential between stator and rotor magnetic field and the stator q and d axis windings have a fixed phase relationship with the rotor magnetic axis which is the d axis in the modeling. The stator equation of the induction machine in the rotor reference frame using flux linkage are taken to derive the model of PMSM as shown in figure (1.3)

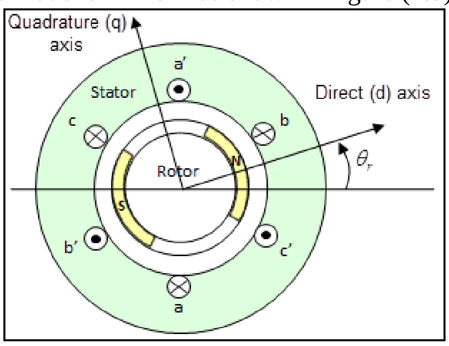

Fig. 1.3: PMSM d-q Reference Frame

Voltage equation is given by:

$$V_d=Rsid - \omega r\lambda q+ d\lambda d/dt \qquad 1.13$$

$$Vq=Rsiq +\omega r\lambda d+ d\lambda q/dt \qquad 1.14$$

Flux Linkages are given by

$$\lambda q=Ld\ iq \qquad 1.15$$

$$\lambda d = Ld\ id + \lambda f \qquad 1.16$$

Substituting the value of λq and λd in equation (1.13) and (1.14)

$$Vd=Rs\ id – \omega r\ (Ld\ iq) + d(Ld\ id + \lambda f)/dt \qquad 1.17$$

$$Vq= Rs\ iq +\omega r\ (Ld\ id + \lambda f) + d(Ld\ iq)/dt \qquad 1.18$$

Now arranging equation (1.17) and (1.18) in matrix form

$$\begin{pmatrix} Vq \\ Vd \end{pmatrix} = \begin{pmatrix} Rs + \frac{dLq}{dt} & \omega r \\ -\omega r & Rs + \frac{dLd}{dt} \end{pmatrix} \begin{pmatrix} iq \\ id \end{pmatrix} + \begin{pmatrix} \omega r\, \lambda f \\ \frac{d\lambda f}{dt} \end{pmatrix} \quad 1.19$$

The torque develop by the motor is given by

$$Te = \frac{3}{2} * \frac{P}{2} * (\lambda d\ id - \lambda q\ iq) \quad 1.20$$

$$Te = \frac{3}{4} P[\lambda f\ id + (Ld + Lq)id\ iq \quad 1.21$$

The Mechanical torque equation is

$$Te = Tl + B\omega m + J\frac{d\omega m}{dt} \quad 1.22$$

Solving from rotor mechanical speed from equation (1.22)

$$\omega m = \int (\frac{Te - Tl - B\omega m}{J})dt \quad 1.23$$

And rotor electrical speed is

$$\omega r = \omega m\ (\frac{P}{2}) \quad 1.24$$

VI. Parks Transformation & Dynamic D-Q Molding

The motor generally works in two state transient state and steady state, the dynamic d-q model is used for study of motor during transient and steady state. It is done by converting the three phase voltage and current into dqo variable by using park transformation [8]. Converting the phase voltage variables Vabc to Vdqo in rotor reference frame and the following equation is obtained.

$$\begin{pmatrix} Vq \\ Vd \\ Vo \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos\theta r & \cos\theta r - 120 & \cos\theta r + 120 \\ \sin\theta r & \sin\theta r - 120 & \sin\theta r + 120 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix} \quad 1.25$$

In constant, V_{dqo} can be converted to V_{abc} as:

$$\begin{pmatrix} Vq \\ Vd \\ Vo \end{pmatrix} = \begin{pmatrix} \cos\theta r & \sin\theta r & 1 \\ \cos(\theta r - 120) & \sin(\theta r - 120) & 1 \\ \cos(\theta r + 120) & \sin(\theta r + 120) & 1 \end{pmatrix} \begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix} \quad 1.26$$

VII. Equivalent Circuit of PMSM

Equivalent Circuit are used for analyzing purpose and simulation of motor. From the d-q model of the motor using the stator voltage equation the equivalent circuit can be derive.

Assuming rotor d-axis flux from the permanent magnet represents the constant current source as describe in the following equation $\lambda_f = L_{dm}I_f$, following figure can be obtain from [7].shows as figure 1.4 and figure 1.5.

Equivalent Circuit are:

1) Dynamic Stator q-axis equivalent circuit
2) Dynamic Rotor d-axis equivalent circuit

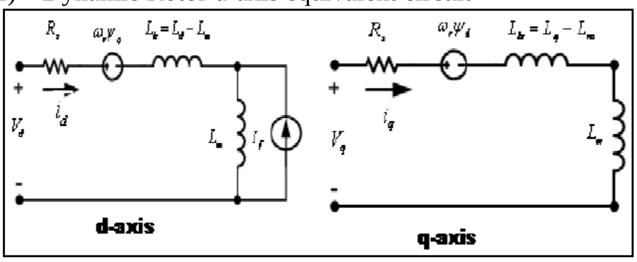

Fig. 1.4: Fig. 1.5:

VIII. Performance Analysis of PMSM

Performance of PMSM is very high than that of Induction motor. According to their performance. The performance of any machine depends on Losses and ability of handling load, A simulation is done in MATLAB to show the three phase current characteristic, Torque, speed characteristic PMSM

PMSM	Rating's
Power -	1.1kw
Voltage -	220 v
Stator phase resistance	2.875 Ohm
Armature Inductance	0.00153 H
Phase	3

Table 1: Rating of PMSM used in MATLAB Simulation

Simulation is done in MATLAB by creating an model of entire PMSM drive system shown in figure 1.6

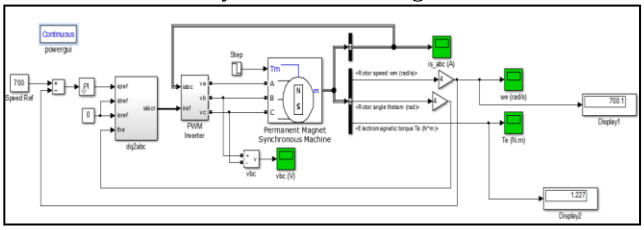

Fig. 1.6: MATLAB Model of PMSM Drive System

A three-phase motor rated 1.1kw, 220 V; 3000 rpm is fed by a PWM inverted. The PWM inverted is built entirely with standard simulink blocks shown in figure 1.7.It's output goes through Controlled Voltage source block before being applied to the PMSM block's stator winding .The applied load torque is set to the machine's shaft is (3 N.m) and steps down to 1.Nm at t = 0.04s.Two control loops are used, the inner loop regulates the motor's stator current and the outer loop the motor speed.

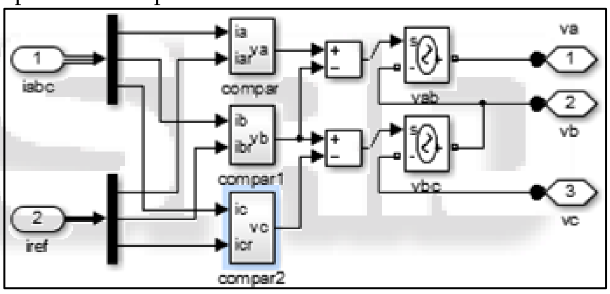

Fig. 1.7: PWM Inverter with Standard Simulink Block

IX. Simulation

Observe that the stator current is quite "noisy" which is to be expected when using PWM inverters. Also the amplitude of the current decreases at=0.04 s, when the load is decreases shown in figure 1.8. It has been observe the noise introduce by the PWM inverter in the electromagnetic torque waveform T_e shown in figure 1.9.However, the motors inertia prevents this noise from appearing in the motor's speed waveform shown in figure 1.10. This is one of the biggest advantage of PMSM as its speed never get disturbed , the speed always remain constant and run's at an synchronous speed .If there is a change in load ,the load angle δ will change but speed will remain constant .

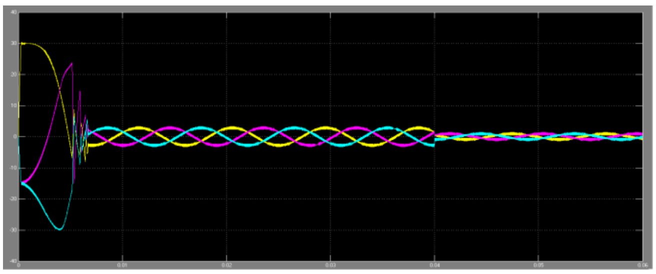

Fig. 1.8: Three Phase Stator Current Graph

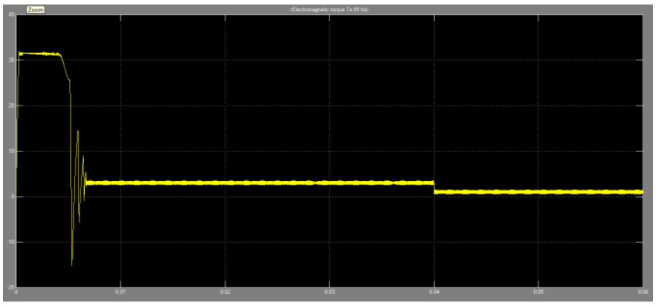

Fig. 1.9: The Electromagnetic Torque Waveform

Fig. 1.10: PMSM Speed Waveform

X. EDDY-CURRENT LOSS IN ROTOR MAGNETS

In every electrical machine there is a loss. Losses are subdivided into three Core loss and Copper loss and Frictional loss. Now core loss consist of Hysteresis loss and Eddy current loss and copper loss is I^2R loss, now compare to other rotating machine loss of PMSM is less because in stator side the loss of PMSM and Induction motor is same as the construction is generally same but there is a difference in rotor side as permanent magnet is used in PMSM. In PMSM the lower and higher order space harmonic rotating at different speed to that of the rotor magnets can induce significant eddy currents in the magnets and incur loss [9]. Method of predicting rotor eddy current loss in analytical way is develop in [9][12]. Assumption is made that the magnet are surface mounted and eddy current are resistance limited, the low permeability and relatively high resistivity of the magnet will limit the amplitude of induce eddy currents and the reaction field produce by eddy current is negligible and the radial thickness and pole arc of the magnets is very small than that of skin depth of eddy current distribution. By formulating the eddy-current problem in the polar coordinate system, the development methods are applicable for both external and internal machines [9][10][12].

XI. THERMAL MODEL OF PMSM

All the losses in the motor is emit out as thermal energy, so monitoring the thermal model is very important during the working of the motor. Excessive heat can damage the winding and can also demagnetize the permanent magnet. Thermal model of PMSM is shown in figure (1.11)

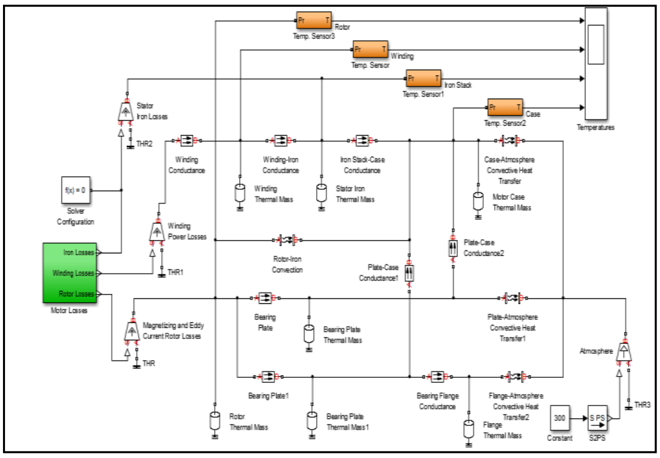

Figure 1.11 Thermal model of PMSM

Rotor loss, Iron loss and winding loss are taken in account, in rotor magnetization eddy current loss is taken in account, brass frictional loss is absent, In Iron loss stator Iron loss is taken account and winding power loss is taken in the system.

Resulting graph are shown in figure's 1.12.

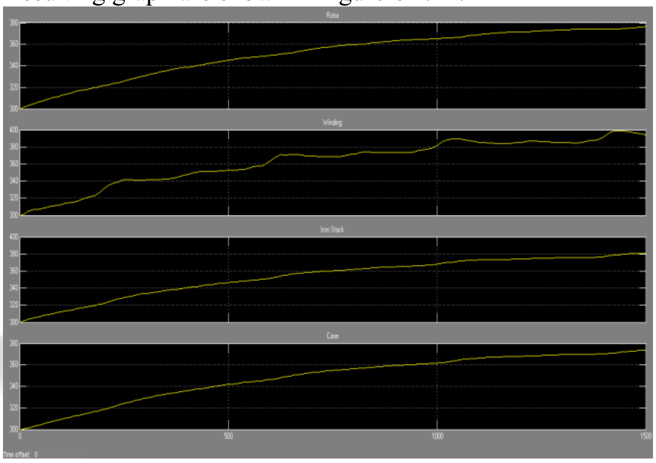

Fig. 1.12: Thermal Graph of Rotor, Winding, Iron stack, Case

XII. ADVANTAGE OVER INDUCTION MOTOR

PMSM have some advantages over induction motor .Which can be very useful in practical purpose, some of the advantages of PMSM are shown below in the table (1.1)

Induction Motor	PMSM
Run's at below synchronous speed	Run's at synchronous speed
Speed is not constant with change in load	Speed is constant
In no load condition power factor is low	Power factor is better than induction motor
To increases the efficiency slip power recovery system is use	Efficiency is much better than induction motor as power loss in rotor is very less

Table 1.1: Advantage of PMSM of Induction Motor

Small size PMSM can deliver very high torque. They are reliable due to absence of brushes and commutator, speed monitoring and regulation can be precisely control, heat generated in stator is easy to remove. As PMSM have this certain advantage's that's why we can use PMSM in heavy duty work and other industrial purpose.

XIII. CONCLUSION

PMSM can give a heavy challenge to Induction motor in many parts of electrical field for its efficient working in compare to the induction motor ,A big issue for induction motor is power factor ,where as in PMSM power factor is not a great issue and PMSM needs a drive system as because it's not self-starting and for controlling, PMSM can be used in Conveyor belts, Elevator planning for high –rise building ,it can work as synchronous condenser .Losses in PMSM is very less compare to Induction motor and the dc supply I not required in the rotor .

PMSM brings a huge change in electrical machine as now days working on permanent magnet are increasing day by day. PMSM motors don't require any of brass maintains, Low noise, and high efficacy.

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