REVIEW OF DESIGN AND PERFORMANCE OF PERMANENT MAGNET SYNCHRONOUS MOTOR

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Abstract: Permanent magnet synchronous motor (PMSM) is an exceedingly efficient motor and is successfully operated in a wide range of speed. Various types of permanent magnet synchronous motors are accessible in the market offering advantages of direct on line starting as induction motor and effectively running on synchronous speed. Major disadvantages of PMSM is uncertainty of successfully synchronization, loading capability during asynchronous as well as synchronous period. The present market potential for motors places a high value of operating efficiency, reliability, variable speed operation, low running temperature, quiet operation and minimum cost. In comparison to induction motor, PMSM provides the peculiarity of consumer prerequisite along with high power density and high power factor. The advancement in the design technologies and magnetic material allows the achievement of souk ambition at even higher temperature without much more permanent magnetization loss. This paper presented the investigations of new structures appearing in scientific literature carried out by the researchers to obtain multi-objective optimal design for PMSM.

Index Terms - Permanent Magnet Synchronous Motors, Axial Flux Geometry, Radial Flux Geometry, Torque, Efficiency Power Factor And Hybrid Models

I. INTRODUCTION

Huge amount of electric energy drawn by the electric derives is gone astray in the form of heat due to nonefficient performance of the drives. In the family of line start motors, the prolific induction motor is one, of which operation is unhealthy and not fit in today’s market trends. The permanent magnet synchronous motor is the only alternative to overcome this disadvantages of line start induction motor [1]. The operation of the permanent magnet synchronous motor comprises two modes, asynchronous mode during which the machine runs as induction motor and synchronous mode during which the motor run at synchronous speed [2]. Certainty of successful synchronization is an important undertaking of researchers and asynchronous torque and magnetic braking torque are deciding factor of success rate. Hybrid electric vehicles (HEV) especially preferred for high speed application ranging from 7000rpm to 16000rpm and faster acceleration are favourable due difficulties of batteries and current lack of an electric vehicles [27]. Design considerations divides permanent magnet synchronous motor into various categories.

II. CLASSIFICATION

On the basis of flux linkage two types of machines are reported - radial flux PMSM and axial flux PMSM shown Fig. 1 & 2 [5]. Two more types of PMSM depending upon the rotor structure available in the market are Line start interior permanent magnet synchronous motor (LSIPM) and surface mounted Permanent magnet synchronous motor (LSSPMSM) [14]. This paper is devoted to provide an overview of the present-day advancement in the design of PMSM.
advantages of reduction in amount of PMs needed[18]. The slotless type machine is not recommended for traction applications because it is subjected to number of stresses[20]

A. Axial Flux Geometry :

The axial flux permanent magnet motor(AFPM) is a better choice in some applications such as in wheel motors of electric vehicles as compared to radial flux machine[6]. The comparison of output parameters presented in the table - I [7] validated the choice of Axial flux motor of its in wheel motors in electric vehicles. The axial flux disc motor proved to be reliable and efficient in applications of low speed and high torque

| Table I: AFPM and RFPM in wheel motors[7] |
| Parameters | AFPM motor | RFPM motor | Requirements |
| Torque     | 219.5Nm    | 207.6Nm    | >107Nm       |
| Power      | 9.24KW     | 8.74KW     | >8.7KW       |
| Mass of motor | 41.58Kg  | 55.24Kg    | <43.125Kg    |
| Specific power | 222.24W/kg | 158.16W/kg |              |
| Rim dia    | 14"       | 15.36"     | -            |
| Efficiency | 89.8%      | 77.8%      | -            |

An axial flux permanent magnet motors have disc shaped stator and rotor cores with single rotor disc sandwiched in two stator discs or single stator disc in between two rotor discs. The flux crosses the air gap axially and passes through the core in the circumferential direction[8]. The m.m.f has the form of quasi square wave. The advent of high field rare earth permanent magnets has opened new doors for novel machine topologies with improved performance[18]. The AFPM motors can be an alternative to conventional radial flux PM motors particularly for low speed and high torque electrical drives.

A number of configurations have been proposed[10-19]. Such as internal rotor[13], internal stator[11], multidisc type, slotted or slotless and rotors with interior or surface mounted permanent magnets[6] are also available. Various design parameters such as outer diameter, inner diameter, inner to outer diameter ratio, number of slots magnet pitch and skewing affect the performance of the machine and the careful choice of the values of these parameter is the main justification of the suitability of an AFPM motors[21]

The travelling wave modelling of AFPM motor with slotted stator geometry and analysis including saturation in stator iron and effects of slot leakage reveals that square flux wave in teeth produces a triangular wave in the yoke which lead to higher flux density in yoke(1.9wb/m²) as compared to teeth(1.6wb/m²)[8]. The laboratory machine results and predictions of computer based model shown in fig. 3 & 4[8] is less convincing. The “V” curves produced by conducting no load testing differ from calculated as presented in fig. 4[8]. The Geometry offers leakage flux reduction to large extent even rotor slot leakage is totally eliminated but only stator slot leakage and stator coil end leakage remains[22].

The skewing of permanent magnets has proved fruitful in reducing cogging torque effect.[8]

Slotted stator axial flux geometry suffers from a major drawback of under utilization of stator winding due to end winding length[18]. The slotless axial flux motors proved good interest in high performances drives[10][11][23] and particularly designed preferred for applications characterised by low speed and high torque to weight ratio[12][24]. The slotless axial flux machine having two rotor discs sandwiching one stator shown in fig. 5[18] has advantages of utilization of both working surfaces of stator core as compared to conventional machine. The stator has toroidal winding placed on iron strip[25]. The rotating rotor discs acting natural fans serving for cooling and thereby lowering the working temperature and permitting higher permissible electric loading. The machine torque as presented by equation (1) is function of outer diameter[18]

\[ T = A R_0^{3.5} \quad \text{(1)} \]
Where ‘A’ is coefficient that depends upon thermal and structural parameters and $R_o$ is outer diameter of machine that will be significant design parameter to obtain higher torque to weight ratio principally applicable in electric vehicles. The variation of torque at rated current and 50% loading with outer radius is shown in fig. 6[18]

![Fig. 5 Two rotor discs sandwiching one stator](image)

There is another factor $K_r$, the ratio of inner to outer radius of machine on which the machine dynamic characteristics depends[24]. The choice of value of $K_r$ is used to maximise torque, torque to weight ratio and efficiency. The variation of these performance parameters with $K_r$ shown in fig.7[18]

![Fig.6 Variation of torque at full and half load with outer radius](image)

Radial sections of the conductors are not in same electromagnetic conditions, the fact can be realized from the flux lines for two sections inner and outer radius[25]. The influence of radial variations of magnet pitch on the torque value for converter fed axial flux machine is shown in table-II[25].

The powder iron metallurgy core is used in axial flux geometry for minimizing the cogging torque disturbance [26]. The 2D results of cogging torque with and without modified geometry without considering edge factor of permanent magnets is shown in fig. 9[26]

**Table II** [25] Effect of radial variations of magnetic pitch on torque[25]

<table>
<thead>
<tr>
<th>Type of current</th>
<th>Min. value</th>
<th>Max. Value</th>
<th>Ripple</th>
<th>Mean value</th>
<th>V1 Harmonic peak value</th>
</tr>
</thead>
<tbody>
<tr>
<td>180°, 6.6 A</td>
<td>20.16</td>
<td>21.64</td>
<td>1.48</td>
<td>21.21</td>
<td>0.52</td>
</tr>
<tr>
<td>120°, 8.1 A</td>
<td>20.56</td>
<td>24.70</td>
<td>4.14</td>
<td>22.98</td>
<td>1.98</td>
</tr>
<tr>
<td>180°, 8.1 A</td>
<td>24.7</td>
<td>26.6</td>
<td>1.90</td>
<td>25.99</td>
<td>0.65</td>
</tr>
</tbody>
</table>

![Fig.8 Radial variation of magnet pitch](image)

![Fig.7 Variation of performance parameters with $K_r$](image)

**Fig.8 Radial variation of magnet pitch** [25]

**Fig.7 Variation of performance parameters with $K_r$**[18]

Due to radial variation of magnet pitch in the slotless permanent magnet axial flux motor, the active conductors are subjected to different conditions of magnetic field along the radial length[25]. From the electromagnetic considerations, the magnets side edges should sweep the stator conductors during the motion all along the height, this involves annular sector shapes of permanent magnets. A typical three phase 8-pole with one coil per pole per phase is shown in fig.8[25]. The left part shows cut view of stator and right shows one of the rotors The $Z$-axis coincides with radial axis and active parts of conductors parallel to $r$-axis.

![Fig.9 Cogging torque with and without modified geometry](image)

**Fig.9 Cogging torque with and without modified geometry** [26]
In spite of disadvantages of decrease in output torque, the short pitched stator winding design has been used to reduce both harmonic component and length of end windings\[27\]. 150\(^{\circ}\) magnet span and one slot pitch shaving of magnet resulted in ripple free torque and decrease in losses preferably in high speed applications.

In stator core, M-4 grain oriented silicon steel is used to reduce stator core losses. Moreover magnet excitation is kept low around 0.73T and low flux density in stator core about 1.2T is preferred. The Steinmetz equation given by (2) describes the specific core loss in W/kg \[28\] 
\[ p_{co} = 0.014492B^{1.8}f + 0.00004219B^2 f^2 \]  
\[ \text{-----}(2) \]

The difference in the measured and predicted stator core losses are due to unepredicted hysteresis loss caused by anisotropy of M-4 steel.

The eddy current loss is major component of total rotor core losses. It has further divided into three parts, no load eddy current loss due to the existence of slots, on load eddy current loss caused by mmf winding harmonics and on load eddy current losses induced due the presence of time harmonics of supply system in inverter fed motors\[29\]. The rotor losses can be calculated from static FE solutions \[30\] using the positional magnet flux density waveforms. The concentrated windings produce large amount of current linkage harmonics passing across the permanent magnets causing large eddy currents. The large slot opening causes flux density variations that turn out eddy current losses in permanent magnets\[31\].

The analytical methods \[32\] \[33\] used to calculate losses in radial flux permanent magnet machine ignore the effect of slot opening whereas in axial flux machines losses are estimated by taking into account the slot opening using Heller and Hamat’s equation \[34\]. The eddy current losses evaluated using three method are no load method for stator slot opening losses magneto dynamic(unmagnetized magnets) method for losses due to stator mmf space harmonics and load method for both components simultaneously without considering influence of skin effect and saturation\[29\] \[31\] \[41\]. The effect of sintered segmentation is shown in fig.10 \[31\].

The relation used to estimate eddy current losses in magnets using FEA \[31\] is given (3) 
\[ p_m = \int p_m j^2 dV \]  
\[ \text{-----}(3) \]

where \( p_m \) material resistivity V the volume and \( j \) current density

The second problem in high speed machines is significant mechanical vibrations and stresses experienced by permanent magnets. These produced by attractive forces between rotor permanent magnets and stator core and centrifugal forces. The glue used for fixing permanent magnets in low speed machines can withstand maximum force density around 5N/mm\(^2\).\[27\]. The testing upto 120\(^{\circ}\)C showed the impossibility of protection of permanent magnets. The adhesive force of glue is increased by nickel coating of the magnets and protection is provided by placing fibre glass rim over rotor magnets. By doing this the stress value is increased to 1G Pascal\[27\]

Thermal conductivity of NdFeB is relatively poor (9W/mk)\[31\] which is problematic for surface mounted magnet geometry because of large eddy current losses in the permanent magnets. High power loss density leads to fatal temperature rise and hence demagnetization and lower the efficiency of sintered NdFeB bulky permanent magnet machines. The difficulty is shorted out by replacing sintered NdFeB permanent magnet by plastic bonded magnets operated above 100\(^{\circ}\)C \[37\] but suffer at the same time from smaller remnant flux density (0.65T) and coercive force force(403KA/m) compared to sintered NdFeB 1.05T and 800KA/m\[36\]. Also energy product of plastic bonded magnets is lower (40-90 KJ/m\(^3\) ) whereas sintered NdFeB permanent magnets have 190-380 KJ/m\(^3\) \[29\]. This leads to increase in size of machine and there by centrifugal forces.

**B. Radial flux Geometry:**

The line start permanent magnet motor combines the features of both permanent magnet rotor for synchronous motor operation and squirrel cage induction motor during the asynchronous motor operation and the machine has the ability to direct line start therefore\[42\]. The proper volume ratio
between permanent magnets and squirrel cage is the best response to the challenge of reduced construction and running cost along with better performance[43]. Further with elimination of magnetizing current resulted into improvement of operating power factor and reduction in stator windings losses[44]. Two design of LSPMM recorded in the literature are surface mounted permanent magnet machine and interior permanent magnet machine shown in fig.12 a&b [45]. The challenge of high efficiency motoring over the world has been responded by the LSPMM which has boosted by the dramatic improvement in the magnet properties of the permanent magnets used and tone motor energy efficiency class globally [46-47]. The possibility of high temperature operation without demagnetizing of the PMs, the LSPMM gained the popularity

C. Interior Permanent Magnet structure:
The interior magnet design as shown in fig.12.a[45] has embedded magnets [46-47]. This type of configuration suffer less from demagnetization problem. This design is also called convex design[50] During asynchronous period from standstill to just reaching synchronous speed, the accelerating torque is the resultant of two torques- cage torque and braking torque[51] given by the equations(4&5) [45]

\[
T_c = \frac{1}{2} Re(\lambda_{dc}I_{qc} - \lambda_{qc}I_{dc}) \quad (4)
\]

\[
T_m = \frac{m}{2} Re(\lambda_{dm}I_{qm} - \lambda_{qm}I_{dm}) \quad (5)
\]

During synchronous period the braking torque almost reduced to zero value and the main torque is alignment torque of permanent magnets and reluctance torque produced due to the saliency factor of rotor structure, both the torque are given by equations(6&7)[52]

\[
T_{ema} = \frac{P}{2}\omega E_0 I_q \quad (6)
\]

\[
T_{rel} = \frac{1}{2}\omega (X_d - X_q) I_d I_q \quad (7)
\]

The IPM suffers from serious drawback of higher leakage flux and thereby less air gap flux density. But the cogging torque developed is less and subjected to less vibrations so less noisy operation. The synchronizing capability of IPM is better but it hand has small synchronous loading capability[45]. Numerous rotor topologies of IPM are proposed in literature in last about 30 years for improving both asynchrnonous and synchronous operations. There exists wide trade off between the two operations and then techno-economic feasibility of the machine is evaluated [53]. The various rotor structures based on the permanent magnet arrangements [54-55] is shown in the fig.13[1/4]

![Fig.12 Interior Permanent Magnet Motor](image)

![a) Interior type b) Surface type](image)

The results showing the comparative performance of these six models simulated in Maxwell has been demonstrated in table III & IV[54]. The radial arrangement provided better output parameters

<table>
<thead>
<tr>
<th>Rotor Type</th>
<th>Synch. Performance</th>
<th>Starting Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\eta$ (%)</td>
<td>$\mathrm{Pr}$</td>
</tr>
<tr>
<td>Spoke</td>
<td>91.6</td>
<td>0.997</td>
</tr>
<tr>
<td>radial</td>
<td>92.12</td>
<td>0.995</td>
</tr>
<tr>
<td>U</td>
<td>91.41</td>
<td>0.995</td>
</tr>
<tr>
<td>V</td>
<td>92.05</td>
<td>0.995</td>
</tr>
<tr>
<td>W</td>
<td>92.03</td>
<td>0.992</td>
</tr>
<tr>
<td>Swastik</td>
<td>92.06</td>
<td>0.996</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No Load Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_0(A)$</td>
</tr>
<tr>
<td>Spoke</td>
</tr>
<tr>
<td>radial</td>
</tr>
<tr>
<td>U</td>
</tr>
<tr>
<td>V</td>
</tr>
<tr>
<td>W</td>
</tr>
<tr>
<td>Swastik</td>
</tr>
</tbody>
</table>

The effect of shape of magnets using arc, rectangular and parallelogram type of magnets has been evaluated and observed that spoke arc magnet combination is superior in comparison to others[54].The proposed arrangement is shown in fig.14[54] The prototype has drawn 13% lower full load current and deliver 16% more output.
Repeated five full load tests of duration 8 hours each, shows no deterioration of the magnets. The little decrease in open circuit voltage has been recovered when machine resumed normal temperature[54]. The model has better power factor, less rated current and high energy saving prospective. Double layer magnet arrangement in interior permanent magnet motor with flux weakening control adopted to increase speed range of motor [56]. The arrangements “I” type[57], “V” type [58-59] and double layer [60-62] shown in fig.15[56] are generally used to increase the reluctance torque.

The results clarified that V type arrangement has wide range of speed with high efficiency and maximum torque at low speed due to lower $L_d$ and high $L_q$ is acceptable[56].

The new rotor geometry in fig.16[48] has combined advantages of conventional radial and circumferential geometries. It shows a good potential of energy saving and improvement in power factor.

The comparison of various output parameters shown in fig. 17[48] with radial bonded spoke type and new geometry verifies the better performance of new geometry.

The new hybrid rotor geometry of permanent magnet synchronous motor used both ferrite and bonded rare earth magnets with the objective to increase air gap flux density and thereby output power[63]. About 30% higher flux density is achieved as compared to conventional circumferentially magnetized rotor for same magnet volume. The effect of magnet size, location and angle of inclination evaluated using FEM and Maxwell. Best compromise between cost and performance has been achieved.

Super premium efficient line start up permanent magnet synchronous motor design [64] shows increased efficiency level with reduced size and
weight. Three rotor configurations namely parallel magnet path, series magnetic path and combined magnetic path shown in fig. 18[64] have been principally investigated with the help of FEA. Comparison of results from table-VI[64]) verified the improvement in design.

**Table VI** Comparison of LSPMSM(IE4) and IM(IE3)[64]

<table>
<thead>
<tr>
<th>Performance</th>
<th>LSPMSM</th>
<th>IM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>93.53%</td>
<td>92.40%</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.98</td>
<td>0.88</td>
</tr>
<tr>
<td>Starting torque(PS)</td>
<td>218</td>
<td>180</td>
</tr>
<tr>
<td>Starting current(A)</td>
<td>252.1</td>
<td>232</td>
</tr>
</tbody>
</table>

The magnets are mounted on the surface of the rotor[65-66][45]. The geometry offers less leakage flux and reluctance consequently air gap flux density is high in comparison to IPM of same size therefore delivers large output power. But regrettably suffers from increased cogging torque more vibration and noisy operation due to bigger reluctance forces developed. The machine with surface mounted design has smaller asynchronous loading capability but large synchronous loading capability.

![a) Rotor with parallel magnet path](Image)

![b) Rotor with series magnet path](Image)

![c) Rotor with combined magnet path](Image)

**Fig.18 Super premium design of PMSM[64]**

The various design strategies investigated have their own advantages and disadvantages but hybridization showed observable effect on the performance of the PMSM.

**CONCLUSION**

This paper has presented an overview of various design strategies used in the design of permanent magnet synchronous motor developed by the researchers in the past and the effect of variation of geometric parameters on the performance of the motor. Categorization on the basis of flux linkage, magnet positions, arrangements and type of magnetic material used for reducing size and cost of the machine has been analyzed. For instance, the axial flux motor has developed high working torque, higher torque to weight ratio for same number poles and slots however these are not suitable for high speed drives, on the other hand the radial flux geometry with surface mounted magnets has advantages of high air gap flux density and high synchronous loading capacity though it suffers from large vibration and noisy operation. Similarly interior permanent magnet synchronous motor is less subjected to cogging torque and demagnetizing problem but has the weakness of low synchronous capability and high leakage flux. The very little efforts has been made to combine the features of two or more machines in the literature. The hybrid model using two types magnets yield better results in comparison to conventional model. We are working on the newly proposed model that will combine the features of axial flux geometry as well as radial geometry to improve the asynchronous and synchronous loading capability of the machine. The model mingle the feature of interior permanent magnet motor and surface mounted geometry that will yield better solution to cogging torque reduction. The results of combining the features will certainly give the birth to new generation of synchronous motor.

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