Comparative Analysis of Surface Mounted and Interior Permanent Magnet Synchronous Motor for Low rating Power Application

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Abstract. In this paper a comparative analysis is reported between Surface Mounted Permanent Magnet (SMPM) and Interior Permanent Magnet (IPM) Synchronous Motor for low Power rating application using ANSYS Software. In this study, a 0.55Kw, 220V rated Permanent Magnet Synchronous Motor (PMSM) with two different structures is considered. Here both electromagnetic (i.e. Air gap magnetic flux density) and electromechanical properties (i.e. torque) are considered for obtaining the target. In addition, Iron loss and is also involved for comparison. The results of the analysis were confirmed by Finite Element (FE) Analysis and were based on a simplified analytical model based on a given rating. Results obtained through this method, for validated with the result reported in the literature. Further modification is also done in the parameters and those results are also reported.

1. Introduction
The advancement of power electronics in recent years has paved the way for the use of inverter control in large-scale induction machines [1]. These are most frequently used for all kind of speed Applications like in wind farm. It affects the economic graph of the country. Many Literatures have different motor design to minimize motor size and provide compact size with light weight function to a motor. Focusing on the small size and low cost, Permanent Magnet (PM) based Motors are introduced in High speed applications in [2]. This introduces a magnetic circuit into the motor which is also elaborates in [3]. These machines outperform traditional induction machines in terms of performance. In comparison to current motors in the industry, it has a higher efficiency and torque density[4]. The primary benefit is that they are smaller due to the substitution of field winding with PM. Since there is no field winding, there are less losses and a higher efficiency [5]. The existence of a PM influences or regulates the motor's output actions. It means that the efficiency of the machine under investigation is primarily concerned with the machine's design features and the various types of materials used in various parts of the machine, such as Ferromagnetic and PM [6]. This design features includes slot height, position of magnet, air gap between stator and rotor core, slot wedges, shape of magnet, types of slot(open, close or semi close) etc.. These characteristics are also responsible for harmonics, noise, vibration, and increased pulsation of signals of the machine's rotor and stator [7][8]. So Most of the recent research mainly focused on these two things i.e. Modification in machine structure and Material used for it[9]. This research has an impact on the multiple quantities of primary concerns such as power, power factor, output torque, weight, losses, cost and efficiency etc.[10]. Along with these performance characteristics, it also affects the Electromagnetic field properties of machines which also influence machines output. Undoubtedly, the magnetic material assumes a significant role, additionally in the improvement of a motor’s performance. With respect to performance goal, the main features of it are relative or magnetic permeability and its losses[11]. Interior winding designing such as concentrated and distributed is also affect machine performance[12]. Operating temperature is also decided by material properties and designing features of machines[13]. The most frequently used designing in PM machines are a) Interior Permanent...
Magnet (IPM) and b) Surface Mounted Permanent Magnet (SMPM) machine explained in [14]. This classification is signified by PM position. From different literature study it is very clear that this constructional modification provides many advantages and disadvantages with respect to each individual. Like SMPM has easy construction compare to IPM. Similarly IPM has higher overload capability than SPM due to independent of applied current [14]. It decides the total flux linkage, leakage flux and magnetic field intensity inside the machine. An exhaustive comparison between both IPM and SMPM has been done in [15]. To improve the efficiency of motor, much modification in Rotor structure is taken place like v-shape [16]. Except this, many linear Permanent Magnet motor are developed [17]. But there is no elaboration regarding magnetic field density characteristics of Permanent Magnet based both motors with respect to different constructional parameter [18]. As magnetic field parameters also affect the motors performance characteristics, it can be possible to compare the performance of IPM and SMPM on the basis of field parameters. Here magnetic parameters changes with respect to designing parameters are discussed. Now days to reduce the time consumed in practical, the principle electromagnetic analysis is performed through commercial analysis software [19]. To reduce the simulation timing, 2D analysis is utilized compare to 3D [20]. Many numerical methods are eligible to solve this 2D analysis of Magnetic fields attributes but Finite Element Analysis (FEA) is more appropriate compares to others [21]. So Software like ANSYS has inbuilt FEA solver. To get magnetic field solution in corresponding software, Maxwell’s equations are solved using FEA [22].

Here, comparison of SMPM and IPM having same rating with constructional features has been done on the basis of its air gap magnetic flux density due to PM, its output torque performance etc. Section 2 contains the overall mathematical back ground behind electromagnetic parameter calculation. Section 3 includes Motors design details with problem formulation. Section 4 elaborates the comparison between SMPM and IPM on the basis of motors operational characteristics.

2. Theory and mathematical back ground
This section contains the theory and mathematical background behind the whole analysis of Permanent Magnet Synchronous Motor. To analyze magnetic field and its related components, solving of Maxwell’s Equation is necessary. All these equations are given bellow from expressions (1) to (4).

\[ \nabla \times \vec{H} = \vec{J} \quad (1) \\
\nabla \cdot \vec{D} = \rho \quad (2) \\
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3) \\
\n\nabla \cdot \vec{B} = 0 \quad (4) \\
\]

where \( \vec{H} \) is the magnetic field vector, \( \vec{J} \) is the current density vector, \( \vec{D} \) is the electric displacement vector, \( \rho \) is the electric charge density, \( \vec{E} \) is the electric field vector, \( \vec{B} \) is the magnetic flux density vector, and \( t \) is the time.

To solve Maxwell’s equations, it is better to convert field vector into potential vector. It provides appropriate path for solver to get the solutions of it. Here also it is necessary to change, the above magnetic field equations into its potential vector \( \vec{A} \). Considering above equations, equation (5) to equation (7) are derived.

\[ \nabla \times (\nabla \times \vec{A}) = \mu_0 \vec{J} \quad (5) \\
\n\nabla \times \vec{E} = -\frac{\partial (\nabla \times \vec{A})}{\partial t} \quad (6) \\
\n\nabla \cdot (\nabla \times \vec{A}) = 0 \quad (7) \\
\]
For 2D magnetic field analysis, Maxwell’s equations are solved using different co-ordinate system. According Cartesian co-ordinate system, Magnetic potential vector $\mathbf{A}$ has only z-axis component. Similarly $\mathbf{J}$ also have only z-axis component. So Magnetic flux density ($\mathbf{B}$) is determined by solving Maxwell’s equations. In Cartesian co-ordinate system, for 2D analysis it has both x-axis and y-axis component ($B_x, B_y, 0$). In polar co-ordinate system, Magnetic flux density contains two components i.e. Tangential ($B_t$) and Radial ($B_r$). So Total air gap magnetic flux density is equal to

$$\mathbf{B} = \sqrt{B_r^2 + B_t^2} \quad (8)$$

Generally For any AC PM machine, its electromagnetic torque can be expressed as follows:

$$T = \frac{3}{2} p (\Psi_{PM} i_q + (L_q - L_d) i_d i_q) \quad (9)$$

To calculate Torque of motor in 2D analysis, Maxwell’s stress tensor force equation is used which is given [20] in equation 9.

$$T_e = \oint \mathbf{r} \times \mathbf{\sigma} \cdot dS = \oint \mathbf{r} \times \left[ \frac{1}{\mu_0} (\mathbf{B} \cdot \mathbf{\hat{n}}) \mathbf{B} - \frac{1}{2\mu_0} \mathbf{B}^2 \mathbf{\hat{n}} \right] \cdot dS \quad (10)$$

Where $\mathbf{r}$ is the unit vector, $\mathbf{B}$ is the magnetic flux density vector in the middle of the air gap, $\mathbf{\hat{n}}$ is the unit normal vector of the interaction surface, and $\mathbf{\sigma}$ is the Maxwell’s stress tensor of r-coordinate of the cylindrical coordinate system.

Similarly Magnetic field distribution is described with the expression given below [23]

$$\nabla^2 A + \gamma \mu \frac{dA}{dx} = -\mu_0 \nabla \times M \quad (11)$$

Where $\nabla^2$ is Laplacian, $A$ is the magnetic vector potential, $\mu_0$ is the free space magnetic permeability ($\mu_0=4\pi \times 10^{-7}$ H/m), $\gamma$ is the electrical conductivity and $M$ is the magnetization vector.

3. Designing of two motors

| Table 1. Specification of PMSM |
|-------------------------|----------------|
| **Quantity**           | **Value**     |
| Output Power           | 550 watt      |
| Output Torque          | 3.01Nm        |
| Line voltage Rating    | 220 volt      |
| Stator Resistance      | 2.16 ohm      |
| Synchronous speed      | 1500 rpm      |
| Electrical Frequency   | 50 Hz         |
| Phase current          | 1.6 amp       |
| Relative permeability of NdFeB30 | 1.044 |
| Relative permeability of M36 | infinity |

SMPM and IPM motor designs are considered here with the same rating and geometry parameters. In both cases, a 3-phase 4 number of poles machine with a power rating of 0.55kW is considered, i.e. a low-power machine topology is investigated. It consists of 24 numbers of stator slots having voltage rating 220volt. All these rating with designing parameters of Stator and Rotor of motor are given in following tables. Table 1 contains the specification of PMSMs operations. Table 2 and Table3 contain the constructional features of Stator and Rotor design.
The following Figure (1) and Figure (2) provide a detailed description of the Stator and Rotor designs. A general cross area perspective on the inspected SMPM Motor is appeared by Figure (1), in which fundamental mathematical boundaries are additionally portrayed. Moreover, a cross segment of the motor with itemized mathematical attributes of the stator slots is introduced in Figure (2). The Stator consists of a full pitch distributed lap winding. Stator’s core outer diameter is 120 mm, Rotor’s core outer diameter is 67 mm and motor’s active length is 65 mm.

All geometrical parameters of slot along with winding design of Stator are same in both types of Motors. Similar to SMPM, designing of IPM motor is given in Figure (3). In this case Permanent Magnet is situated on the surface of the Rotor i.e. it is considered under interior designing of Rotor. In the air gap region of Rotor and Stator, there is no presence of PM.

### Table 2. Stator Design Details

| Quantity                                    | Value     |
|---------------------------------------------|-----------|
| Outer diameter of Stator core               | 120 mm    |
| Inner diameter of Stator core               | 75 mm     |
| Active length of Stator core               | 65 mm     |
| Stator slots number                         | 24        |
| Opening width(Bs0) of slot                 | 2.50 mm   |
| Top width(Bs1) of Slot                     | 5.60 mm   |
| Base width(Bs2) of Slot                    | 7.60 mm   |
| Teeth width of Stator                      | 4.70 mm   |
| Slot height(Hs2) of Stator                 | 13.50 mm  |
| Tooth tip height(Hs0) of Stator            | 1.50 mm   |
| Stator tooth slant height(Hs1)             | 0.1 mm    |
| No. Of conductors/slot                     | 59        |
| Diameter of Wire                           | 0.9116 mm |
| Area of Wire                               | 0.6527 mm²|

### Table 3. Rotor Design Details

| Quantity                                    | Value     |
|---------------------------------------------|-----------|
| No. of permanent magnets                    | 4         |
| Rotor outer diameter                        | 71 mm     |
| Shaft diameter                              | 26 mm     |
| Rotor core active length                    | 65 mm     |
| Permanent magnets width                     | 3.50 mm   |
| Air gap length                              | 0.5 mm    |
| Pole arc/pole pitch ratio                   | 65%       |

To dissect the performance of this two designed of PMSM machines; FEA is completed by using ANSYS Software. Through ANSYS software, modelling and parametric analysis is considered to acquire the motor Performance. Here the parametric process is mainly focused on the shape and size of the Permanent Magnet, its position with respect to Rotor, the width and depth of the opening of the Stator slots and shape of Rotor; the optimization results are acquired by using ANSYS software.
After designing completed based on Table 2 and Table 3, set the winding and material property. Table 1 contents the details of specification of motor. In the choice of material properties, relative permeability assumes a significant role. The sort of the magnetic circuit material used here is M36, its normal B-H characteristics are shown in Figure (4). Figure (5) shows the permeability (µ) of M36 silicon steel with respect to magnetic Flux Density (B). After reaching the saturation point, the permeability of magnetic material decreases to 0. Then set the magnetic field as a nonlinear constant. NdFeB35 magnet shows an almost linear performance in the operating range with a relative
permeability near to free space (i.e. $\mu_r \approx 1$). Because of symmetry of the structure, analysis of $\frac{1}{4}$th part of whole model is carried out. It will decrease the number of finite element and save the simulation calculation time. Here in FEA, 1000 number of elements is considered for each part of the motor design like for coil, magnet and core during Meshing as shown in Figure (6). Though the number of element decides the simulation timing, try to consider the less number under Normal sizing of Mesh. After meshing, Finite element analysis is carried out to obtain the simulation result of Motor.

4. Performance comparison factor

4.1. No load Performance
In case of no load condition, Stator does not create magnetic field. So the no-load field is created by the Rotor’s Permanent Magnet. The electromagnetic field simulation of the three-phase AC Permanent Magnet Synchronous Motors in Figure (1) and Figure (3), simulation results can be appeared in Figure (7) and Figure (8).
These figures compare the magnetic flux lines distribution throughout surface of SMPM and IPM motor. From the simulation, it is clear that in case of IPM, Magnetic flux lines can easily passes through the air gap as compare to SMPM due to the absence of PM on outer surface of Rotor. It means leakage flux in IPM motor is less compare to SMPM. Similar to radial flux lines, Figure (9) and Figure (10) describes the comparison of magnetic flux density between SMPM and IPM motors. In case of magnetic flux density analysis, it is cleared that the silicon sheet near PM is highly saturated.

For SMPM motor, saturation level is more compare to IPM motor due to presence of PM near to Stator core. Under constant air gap of 0.5mm between Stator and Rotor, the air gap flux density is also affected by position of Permanent Magnet.
than IPM. But in SMPM, the open slot effect is more. So that it will produce more noise, vibration in the motor. As a result of which, ageing effect is more. So to overcome these problem, IPM motor is best which provide linear wave form of air gap flux density compare to SPM motor.

![Air gap Magnetic Flux Density Vs space angle in SMPM](image1)

Figure 11. Air gap Magnetic Flux Density Vs space angle in SMPM

Figure (11) provides the information regarding magnet edging effect with open slot effect. In Figure (12), the depth section is due to opening of slot base of width (Bs0) 2.5mm. Average value of magnetic flux density in case of both SMPM and IPM is elaborated in given Table 4.

![Air gap Magnetic Flux Density Vs space angle in IPM](image2)

Figure 12. Air gap Magnetic Flux Density Vs space angle in IPM

| Motor | Air gap Flux density(T) | Efficiency (%) |
|-------|-------------------------|---------------|
| SMPM  | 0.6807                  | 68.67         |
| IPM   | 0.5741                  | 92.9035       |

Table 4: Air gap Flux Density

4.2. Under Rated Condition
In the rated load, Magnetic Flux Density and phase voltage curve with respect to electrical angle are sinusoidal. From simulation In SMPM, maximum magnetic Flux density is 0.9030T with leakage flux factor = 1 and IPM has a maximum flux density value of 0.58T with leakage flux density factor 1.238. The simulation result are shown in Figure (13) and Figure (14). It is considering same power rating, voltage rating, and designing parameters for both Motors analysis.
From the simulation it is clarified that the efficiency of IPM motor has higher efficiency than SMPM motor which is clearly donated by comparing Figure (15) and Figure (16). Values are depicted in Table 4.
To choose a motor for any application, consider the efficiency and torque characteristics. Figure (17) and Figure (18) explain the Output Torque property of SMPM and IPM with respect to Torque angle. These plots show the torque property with respect to time. From these Figures it can be observed that the both motor’s synchronization is achieved after approximately 0.25 msec.

The average output torque in SMPM is equal to 3.4620 Nm, while the maximum torque during motor’s starting performance is equal to 5.2354 Nm. Similarly for IPM, average value of output torque is 5.9587 and maximum torque is 10.0325Nm. Output torque of IPM is more than SMPM motor. But ripple factor of torque is more because of harmonics presence in supply current. Because of higher value of Efficiency and torque values, IPM motor is more preferable compare to SMPM motor.
In some application, SMPM motor is preferable while considering the core loss. It has less core loss compare to IPM motor in transient condition which is clearly visible in Figure (19) and Figure (20). In case of SMPM, the saturation level of loss is started at 25ms where as in IPM motor case, it is coming around at 40ms.

5. Conclusion
In this paper the output of Surface Mounted and Interior Mounted PM Synchronous Motors in applications with low power rating is compared. The electromagnetic and electromechanical parameters of both motors different depending on design parameters including air gap and operating temperature. Here Analysis shows the IPM has 35.28% more efficiency than SMPM having same rating. It also has more than twice the maximum torque of the SMPM. Despite the fact that SMPM motors have a higher flux density under no load condition, they also have a greater amount of Slot impact in the air gap magnetic flux density. Slot effect is also reveals the harmonic contents in air gap magnetic flux density. It denotes continuous magnetization and demagnetization of Magnet. But to avoid noise and vibration due to more harmonics in Magnetic Flux Density, IPM motor is more preferable for all variety of speed application. Under this study, core loss of IPM is 16.95% higher than that of SMPM because of its end connection.

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