Electromagnetic Design of a 7kW Permanent Magnet Synchronous Motor for a Two-Wheeler

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ABSTRACT

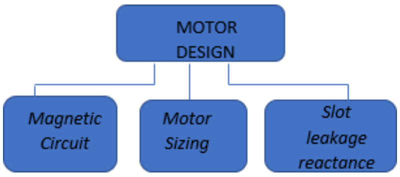
The focus and interest on Permanent Magnet Synchronous Motor has been continuously increasing, thanks to their properties which are deemed suitable for a variety of applications especially in automobiles. This paper presents an approach to electromagnetically design of a 7kW PMSM that will in turn be responsible for propelling a two wheeled electric vehicle. The nominal parameters like air gap, structure dimensions, slot size, pole number, etc have been calculated mathematically during the design of the motor and accordingly a 12s8p Interior Permanent Magnet motor has been presented. The approach taken to make an integrated design has been explained and the results have been quantitatively verified .The proposed design has been optimised and simulated using Flux Motor Software

Keywords: PMSM, magnet, winding, air gap, magnetic circuit, electromagnetic

I.INTRODUCTION

In an era where the industry is gradually shifting towards electric vehicles due to increasing concerns pertaining to climate change, the focus on development and design of motors has increased a lot. The growing demand of electric vehicles has fuelled an increase in the demand of PMSMs. Vehicular motors should have a high power density [1], high torque to current ratio and well as be high efficiency. PMSMs are a very attractive option due to their compactness, high performance and low maintenance. A lot of constraints have to be kept in mind while designing a light weight motor that caters to the requirement and is within a particular cost bracket. Along with this, the primary goal is to develop a highly efficient motor that will in turn contribute to lower losses and lower carbon emissions while reducing the motor volume, decrease the space occupied by it and improve material utilization. Along with this, ease of manufacturability, installation, maintenance, raw material required and the technology used to implement are a few things that are considered while selecting or designing a motor.

The design and analysis of a motor can be divided into 4 sub categories namely preliminary assumptions, electromagnetic design, thermal and cooling analysis and mechanical design and dimensioning. In this paper we focus only on the electromagnetic design aspect. The electromagnetic process can be further categorized into design and calculations of the magnetic circuit, the sizing and the slot leakage reactance.



Firstly we compute and fix the basic geometrical data and the motor topology [2]. According to this, the electromagnetic design and analysis is done. Optimization is a vital part in designing a high performance machine. A variety of applications with different performance requirements may be improved by selecting optimum geometry dimensions, material properties and excitations. In this paper we focus on the electromagnetic design and analysis of a PMSM motor in the electric power train of a two wheeler. It includes the evaluation of various factors including rotor topologies ,winding patterns, air gaps amongst a few. The specifications of the motor designed are mentioned in table 1.

Table 1: Motor Specifications

Peak Torque	32 N.m
Peak Power	7 kW
Speed	2000 rpm
Line current, rms	145 A
Line-line voltage, rms	44 V
Current Density	19 A/mm^2

II. DIFFERENT MOTORS USED IN ELECTRIC VEHICLES

a) DC Motors

These motors were popular before the age of development[3] in the power electronics sector. Ease in control and a robust structure is what made it attractive. But the downsides include their large structure and low reliability. The presence of brushes in them also cause decrease in efficiency and an increase in the cost of maintenance. This also acts as a hinderance to reach the maximum speed. So, these are a good choice in low power applications.

b) Induction Motors

Squirrel cage IMs have a simple yet sturdy structure which has the ability to be to be highly reliable and cheap. The torque produced has a low ripple and this motor can be used in high speeds too. But a relatively complex circuitry , lower efficiency and power density has led to a decrease in it market share.

c) PMSM

PMS motors have overtaken induction motors especially in traction applications owing to their highly efficient energy output [4]. Their high power density and a great torque quality have made it a likeable option to quite a few automobile manufacturers like Toyota and Nissan. But their cons include a complex construction and a high price.

d) BLDC motors

When it comes to high-speed applications, these motors are generally the most suitable. They are capable of performing at high speeds while keeping the weight low. The absence of brushes makes its maintenance easier and cheaper. An average field weakening ability of these motors implies an accurate speed control only at higher speeds. These motors have a better overload capacity than their PMSM contemporary.

Table2: Performance of different motors based on various criteria(1-Best;4-Worst)

Criteria	**Nominal Speed**	**Power Density**	**Efficiency**
DC	4	4	4
PMSM	2	1	1
IM	3	3	3
BLDC	1	2	2

III. MOTOR SIZING

Before we begin the sizing process, we have to keep in mind the required specifications that the motor has to meet including its performance requirements and sizing constraints. Machines are usually sized for the rated torque capability (not the power). And there is a direct dependency of the torque on the rotor volume and shear stress that has to be considered during the sizing. The co-dependency of various other parameters are cited in Table 3.

Table 3: Effect of various parameters on the performance parameters

	COGGING	**SPEED**	**TORQUE**
POLES			
Increased	Decreases	Decreases	Increases
Decreased	Increases	Increases	Decreases
TEETH			
Increased	Decreases	Decreases	No change
Decreased	Increases	Increases	No change
PHASES			
Increased	Decreases	No change	No change
Decreased	Increases	No change	No change

Primary Dimensioning

This step mainly involves fixing the values of parameters like stator outer and inner diameter, the air gap length as well as the core size. Establishing these dimensions basically act as a bas point from where we can build the further constraints. Usually this process starts with a known or maximum value of stator [5] OD which acts as a base for the rest of the parameters. While fixing these ,a few assumptions have to be made regarding the level at which one will be working with the materials and that in turn is dependent on the flux densities in the magnetic circuit.

TRV(Torque/Rotor Volume) is an archaic but dependable method used for the sizing of machines and is related to the air gap shear stress according to the following relation.

$$\mathrm{TRV}=\frac{T}{V_r}=2\sigma \ \mathrm{Nm/m^3} \qquad \text{(i)}$$

Where, σ is the air gap shear stress.

A smaller rotor can be designed for high speed applications for the same power as the torque is quite low.

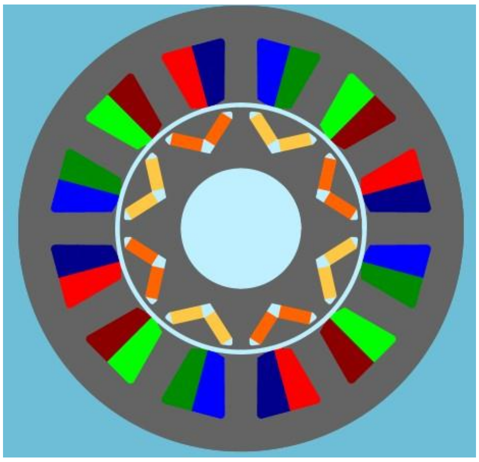


Fig 1: Cross-section of the proposed motor

The cross section of the PMSM motor that is designed for the mentioned specifications is shown in fig 1. We have chosen a 12s8p PMSM based on various iterations as well as analysis of motors that are available in the market.

All the dimensions that play a role in the sizinghave a clear correlation with the required torque specification, air gap stress, air gap flux density and current density, the type of colling employed, and the duty cycle of the load.

Number of Poles

Apart from performing various iterations and analysing the performance variations due to modification in the number of poles, a few guidelines should be kept in mind before fixing the pole number [6]. With the increase in the number of poles, there is a proportional decrease in the amount of iron required in the construction as the total flux is now lay out over more poles and hence reducing the density. And due to the decreased use of iron, the number of windings incorporated can be increased which will also play a major role in decreasing the copper losses incurred. But an obvious downside of a larger pole number is the increased cost of manufacturing.

Table 4: Pole number selection based on rotor/stator dimension (%)

POLES	2	4	6	8	10	12
R/S%	50	53	56	60	65	70

Air Gap

The air gap length is calculated and chosen in such a way that the production of magnetising current is at a minimum value while producing a desirable efficiency. In theory [7] , a small air gap is synonymous to a low magnetising current but it goes along with increased While selecting the winding of a machine, utmost

eddy current losses in the surfaces. In Permanent Magnet Synchronous Motors this air gap is selected after analysing its dependency on mechanical constraints. The magnet dimensions, the inductance and the air gap are all correlated to each other. Usually, the air gap is kept at a minimum to reduce the material required for magnets. The air gap harmonics are also a contributing factor to the losses incurred. The methods taken for calculating the air gap in surface mounted magnets and embedded magnets are a little different. For surface magnets, its calculated using the formula below

$$\delta_{PM} = \frac{h_{PM}}{\mu_{rPM}} + \delta_e \qquad \text{(ii)}$$

Where,h_{PM} is the surface magnet height, μ_{rPM} is the PM relative permeability and δ_e is the corrected air gap with carter's coefficient. On the other hand, for IPM as in this case, they have a different effect on the reluctance and other intricate methods have to be applied.

Winding Selection

The entire foundation of the machine lies on the interaction between the magnetic field and the electric field produced by the windings[8]. The main aspects that are looked into during the selection of the winding pattern is the number of phases(m), number of slots (Q_s) and number of poles(p).

$$q = \frac{Q_s}{mp} \qquad \text{(iii)}$$

importance has to be given to the winding factor (esp.the winding factor of the fundamental,k_{w1}) .During the selection of winding constraints like the number of turns, the number of wires in hand and the pitch should be kept in mind. Also, usually a lower pitch is preferred for a smaller machine and vice versa. The choice of windings (which is broadly categorised into distributed and concentrated windings) is discussed in the following table

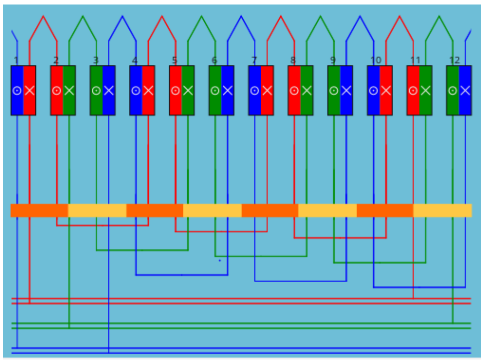


Fig 2: Winding design of the proposed motor

Table 5: Comparative study between distributed and concentrated winding

Distributed winding	***Concentrated winding***
The value of q is an integer	The value of q is not an integer
Longer end windings	Smaller end windings
Produce higher reluctance torque	Produce lower reluctance torque
Have a greater q axis inductance[9] than the d axis inductance which increases the reluctance torque parameter w.r.t saliency	Saliency ratio is comparatively low due to lower difference between d and q axis inductance
Losses are higher	Comparatively lower losses and easier manufacturing
Amount of torque ripple is lower	Higher torque ripple is present
Have higher torque constant and winding factor	Lower torque constant and winding factor
Exhibit more sinusoidally flux density waveforms	Sinusoidal nature of the waveforms is lesser as compared to the distributed windings

Determination of slot dimensions

A prior knowledge about the rotor and stator currents is required before we start with the dimensioning of the slots.

$$I_s = \frac{P}{U_{s,ph} m \eta cos\varphi} \qquad \text{(iv)}$$

Where,
I_s=stator current ,P=shaft power,$U_{s,ph}$=stator phase voltage , η=efficiency, $cos\varphi$=power factor

The flux density always decreases at the slot opening, and therefore it is not easy to define the average flux density of the slot pitch between the stator and the rotor [10]. As the slots will house the windings of the machine, the space required can be calculated by keeping parameters like total magnetising current, the areas of the conductors, the resistive losses and the parallel paths in mind.

$$Area\ of\ conductors, S_c = \frac{I}{a.J} \qquad \text{(v)}$$

Wherein, I stands for the stator current and a and J stand for the parallel paths and the current density respectively.

The next step that has to be employed after this is to calculate the slot area by keeping the space factor into consideration

$$Area\ of\ slot, S_u = \frac{z_Q S_c}{k_{Cu}} \qquad \text{(vi)}$$

Where, $k_{Cu,s}$ is the space factor which primarily depends on the winding type and material and the voltage level

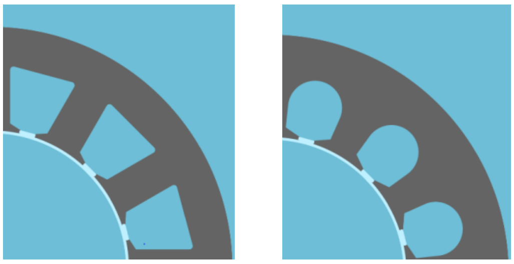


Fig 3: Types of slots available

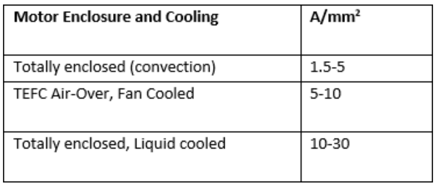
IV.MAGNETIC CIRCUIT

While talking about magnetic circuit of a motor, we generally refer to the magnetic material and the air gap present in the machine and the presence of the magnetizing effect is due to the winding and the magnets involved. In other words, a magnetic circuit can also be referred to as the part of the machine through which the passage of the main flux takes place. In anisotropic machines, it is the rotor saliency that makes the circuit asymmetrical as is dependent on the d and q axis inductance. Generally the number of magnetic paths is more or less equivalent to the number of poles.

Air Gap and Carter's factor

Air gap shear stress is one of the best parameters (especially for PMSM) around which you can manipulate your circuit parameters. This air gap shear stress is proportional to magnetic and electrical loading. The permissible loading levels are based on the cooling and the insulation employed. Effective cooling of a machine increases the loading while decreasing the overall weight of the machine.

Table 6: Preferred phase conductor densities



Motor Enclosure and Cooling	**A/mm²**
Totally enclosed (convection)	1.5-5
TEFC Air-Over, Fan Cooled	5-10
Totally enclosed, Liquid cooled	10-30

a. Electrical Loadability
The current density in the phase conductors is a measure of current loading and determines the duty cycle or/and the cooling requirements. The linear current density around circumference of the air gap can be used as a measure of this parameter.

$$A = \frac{Total\ ampere\ per\ conductors}{Air\ gap\ circumference} = \frac{2mN_{ph}I}{\pi D} \text{(vii)}$$

The unit of measurement for the same factor is A/m as this is the unit for current density too.

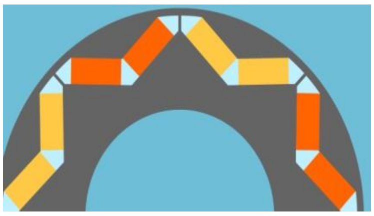
b. Magnetic Loadablilty

Magnetic air gap loading analysis is usually undertaken during sizing that is based on the average flux density in the air gap. The air gap flux density and the supply frequency of the machine determine this parameter. This should be in accordance with the cooling technique employed in the machine

To ease the calculation of the voltage over an air gap, a simple and a uniform geometry is preferable. With the surfaces of the machine being occupied by slots and teeth the calculation of the flux density between the rotor and stator is a bit complicated. The decrease in this value is clearly visible in the slot opening area. So, Carter's factor[11] comes into play during the calculation according to which, the length of air gap increases with increase in the factor.

Magnetic Material

Neodymium magnets are one of the most widely used magnets in motors[12]and their strength has been further enhanced after the development of alloys with rare earth magnets. Neodymium-iron-boron (NdFeB) is one of the popular alloys that have a great performance. Moreover, the downside of pure Neodymium magnets i.e. temperature sensitivity can be improved by the above mentioned method of alloying.



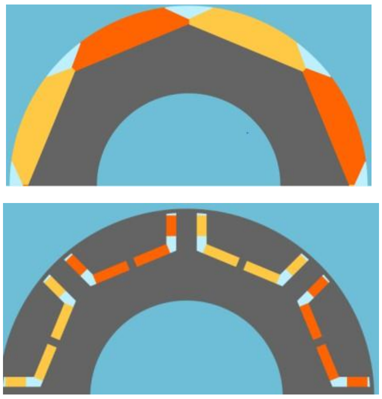
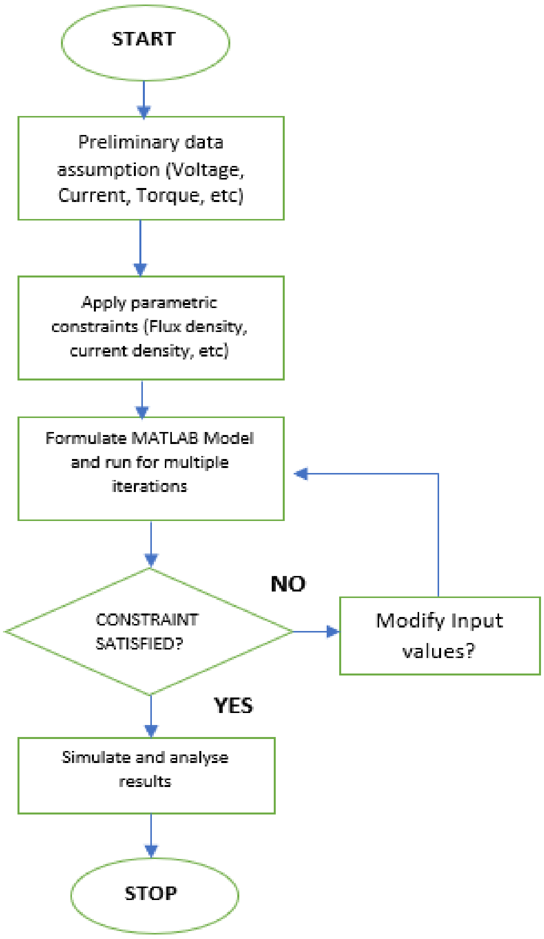


Fig 4:Various magnet shapes

IV. METHODOLOGY

The design of a motor is commenced[13] by defining a set of basic characters like the type of motor required according to the application to get the best possible results, the type of construction method to be employed (external or internal pole, axial or radial flux).



The other vital specifications include rated power, rotational speed, pole pairs, frequency, etc. A MATLAB model was developed to calculate the base parameters using tons of related formulae.

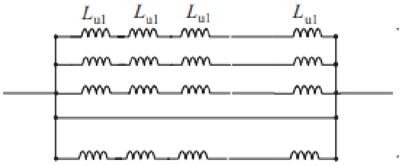
These parametric constraints were applied as inputs in the Flux Motor Software to obtain the proposed design to get the desired results from the motor. Multiple iterations were performed to get to the final values of the various parameters. Apart from this the enclosure class, manufacturability and the standards applied also had to be kept in mind.

VI.LEAKAGE INDUCTANCE

Leakage Flux

The total flux that is present in a machine is constituted by a main field flux and leakage flux. The leakage flux component [14] does not account for the energy conversion process and is generally considered an unwanted phenomenon but it can be used in a positive way too according to the requirement. This component can be found in the stator or rotor windings and even in the magnets present in the machine. The main field flux on the contrary is responsible for electromagnetically connecting the stator and rotor together by passing the air gap of the machine. The primary feature of leakage flux is that it does not cross the air gap of the machine and a few of the leakage flux components are slot leakage flux, tooth leakage flux, end winding leakage flux [15].

Generally , the stator and rotor are placed in a skewed manner to avoid the influence of slot harmonics which is also a contributor of leakage inductance.
When it comes to slot leakage inductance, the underlying cause of this phenomenon is the total current flowing in a slot which is determined by the number of conductors in the slot and hence the current flowing through each of them.



'a' parallel paths

$\frac{Q}{am}$ *slots in series*

Fig 5:Total slot inductance

The geometry of the slot also has a very important role in deciding the slot permeance factor.

VI.RESULTS

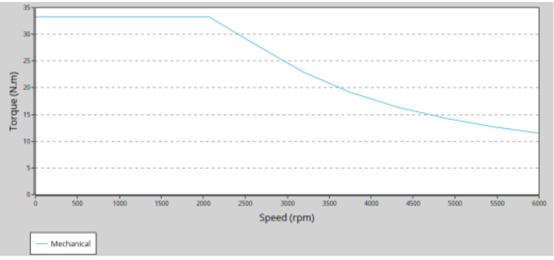


Fig 6: Mechanical torque versus speed

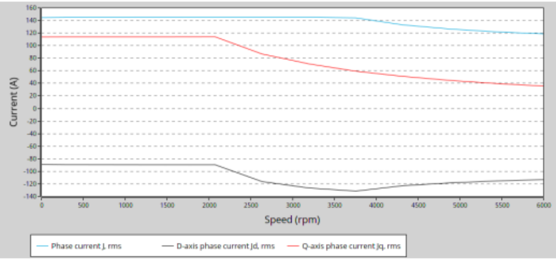


Fig 7: Current versus speed

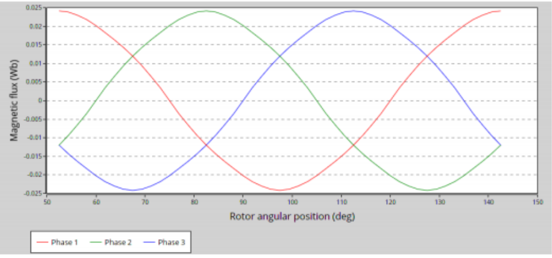


Fig 8:Flux linkage versus rotor angular position control angle

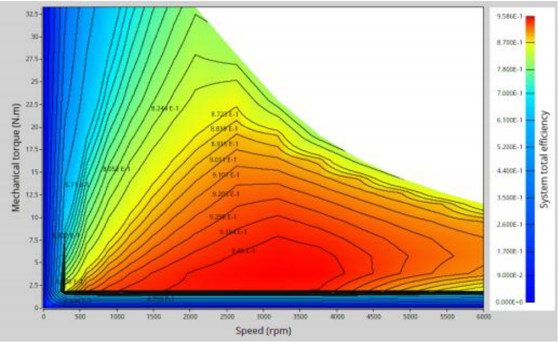


Fig 9: Efficiency in torque-speed area

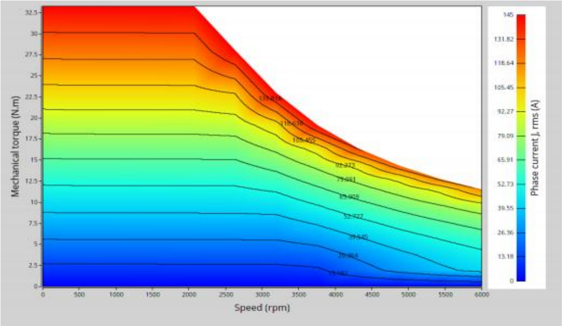


*Fig 10:*Current in torque-speed area

VIII.CONCLUSION

In this paper we have gone through a range of design decisions to be considered while designing a motor for automotive purposes. A 7 kw motor with a high efficiency of 90% was designed ,optimized and analysed using a software and the results were experimentally verified. The entire approach taken while designing the motor has been gone over in this paper methodologically starting from dimensioning to various circuit parameters as well as leakage inductances.

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