Analysis on Design Optimization Techniques of Permanent Magnet Synchronous Motor

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***Abstract*— Electric vehicles, also known as EVs, are gaining popularity because they have several advantages over traditional internal combustion engines. These advantages include lower local pollutants, more energy efficiency, and reduced reliance on oil. In an electric vehicle, the motor is considered to be the "heart" of the vehicle because it is responsible for providing the necessary force for the vehicle to move forward. Induction motors, Brushless DC motors (BLDC), Permanent Magnet Synchronous Motors (PMSM), and Switch Reluctance Motors are some of the varieties of motors that can be found in electric vehicles. PMSM is developed in a more significant manner as a direct result of the increased emergence of new magnetic and earth materials. The Permanent Magnet Synchronous Motor (PMSM) has the highest power density, the highest efficiency, the lowest mass, and the lowest moment of inertia of all the different kinds of motors that are used for the application of electric vehicles. It demonstrates the best performance. The construction of PMSM and the various components that make up PMSM will be the primary emphasis of this report. What effects the various elements have on the torque as well as the other features. Also design optimization techniques used for smoother operation of the motor by reducing the torque ripple. And experiment is carried out in Ansys Electronics in order to monitor motor performance by making use of air-gap design optimisation method.**

***Key Words**: Electric vehicle, PMSM, construction, working principle, torque, torque ripple*

I. INTRODUCTION

Permanent Magnet Synchronous Motor (PMSM) is one of the main types of motors used in Electric Vehicle (EV) for propulsion. PMSM involves low losses as the magnets are permanently magnetized and so the rotor can run synchronously to the switching alternating current. Also, there is no slippage necessary in PMSM as compared to Induction motors therefore heat efficiency is also improved. Though these motors give higher efficiencies as compared other motors it is mandatory to study the torque and power required for vehicle propulsion, and electromagnetic forces produced inside the motor should be studied to analyse electromagnetic vibrations produced.

PMM can be divided into two categories: 1) Internally Permanent Magnetic Motor and 2) Surfaces installed Permanent Magnet Motor. The magnetic component design of an internal permanent magnet motor is shown in Fig. 1. The rotor magnetic circuit is made up of eight laminated silicon steel boxes (shown in Figure 1.1.-d) and eight pieces of embedded permanent magnets (shown in Figure 1.1.-e). The core loss in the motor is kept to a minimum thanks to the material that makes up the stator (Fig. 1.1b), which is a stack of laminated non-orientated grain silicon steel. This stator contains a total of 24 slots, and all of those slots are filled with three-phase dispersed windings in a staggered arrangement. In IPMM, to hold the solid iron part of the rotor nonmagnetic-permissive material (fig 1.1 c and f) are provided to make robust rotor structure and minimize flux leakage at the same time. Screws (figure 1.1 f) made of a material that is not magnetic are used to hold the rotor in place, which helps to prevent the formation of powerful eddy currents that would otherwise occur on the cast aluminium stands (figure 1.1 a and g). (Fig 1.1 a and g).

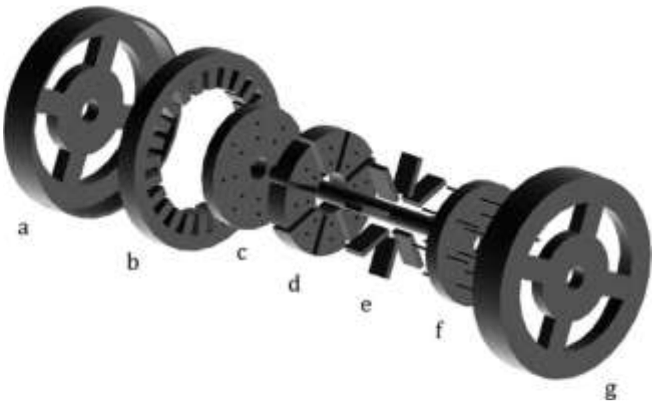

Fig 1.1: Magnetic components of IPM motor

The motor's efficiency is typically influenced by the torque generated, torque ripple, back-EMF value, cogging torque, etc. The torque required to counteract the opposing torque produced by the magnetic attraction between the teeth of the stator and the magnets on the rotor is known as the cogging torque. Cogging torque is an element that should not be present in such a motor's operation. It exhibits the symptom of jerkiness and is particularly noticeable at slower speeds. Cogging torque causes ripples in both the speed and the torque, however at high speeds the motor moment of inertia cancels out the effect. One of the undesired traits of a motor is torque ripple. As the motor shaft spins, it is the regular rise or fall in output torque. The motor moves in an unsteady and jerky manner due to torque ripple. We must comprehend the design of the motor in order to comprehend the necessary changes that had to be done in order to eliminate torque ripple and provide a consistent electromagnetic force that would offer the maximum torque output.

The number of stator slots and rotor poles, as well as the length of the airgap, the size of the magnet, and the construction of the rotor are some of the parameters that determine the torque and other properties. On the basis of these parameters, numerous motor designs are investigated, and the Ansys Electronics programme is utilised for the aim of simulating those designs. Additionally, with this Torque, torque ripple, and cogging torque, etc. parameters are analysed, and the optimal design is utilised in order to obtain desired outputs in an effective manner.

II. LITERATURE REVIEW

For achieving best performance in the motor power and torque output values should be maximum with the minimum torque ripple in order to avoid jerky operation of the vehicle. Investigational studies on the electric vehicle motor were carried out by Khalid G. Mohammed and colleagues [1], who demonstrated the motor operating at three distinct speeds, measured the AC line-to-line voltages, and immediately determined the current that was drawn by the electric lines. The performance equations are used to produce a theoretical calculation of the power input and power output values of the three-phase synchronous motor based on the currents and voltages measured by the sensor. The necessary torque and speed can be determined with the assistance of these experiments.

The researchers Jinlong Zhang, Dejun Yin, and others [2] presented an improved design of a permanent magnet synchronous motor by suggesting that the angle between the permanent magnets of the motor may be modified. Research is being done on the design of the angle between permanent magnets. Magnet angles are maintained within a range of 96 degrees to 136 degrees, as indicated in Fig. 2.1.

As a result of the simulation, it was discovered that when the angle is 96 degrees, the air-gap flux density is low, which causes a leakage in the flux densities of permanent magnets. And when angle is greater than 116° magnetic field is dispersed and magnetic flux leakage increases. When the angle is maintained at 106 degrees, the output torque is at its highest, and the air-gap flux density amplitude is likewise at its highest. As a result, an angle of 106 degrees is selected for the magnets, and the outcomes of the simulation are derived based on this information. After the design was changed, the maximum output torque now stands at 182.31 Nm, the pulsating torque is 6.75 Nm, and the ripple in torque accounts for 3.7% of the average peak torque. The enhancement of the motor's flux density and the reduction of its torque ripple are the primary focuses.

Thanh Anh Huynh and Min-Fu Hsieh et al. [3] investigated the characteristics of IPMSMs. Inside the rotor, a variety of different types of permanent magnets are utilised for the purpose of conducting an electromagnetic performance analysis, which is then utilised to determine the maximum torque production for acceleration. The design of the permanent magnets that were utilised in the investigation of the electromagnetic torque characteristics of the Internal Permanent Magnet Motor is depicted in Figure 2.2.

The capacity of flux lowering is an advantage held by the V-shaped IPMSM. A graph depicting efficiency is plotted for both types of motors by means of FEA and laboratory testing, respectively. It was discovered that IPMSMs had the advantages of having a high PM flux linkage, a low armature current, and an appropriate current angle to achieve the greatest torque. Additionally, it has been shown through comparisons that the efficiency of V-shaped IPMSM is more consistent and superior in comparison with two layer IPMSM.

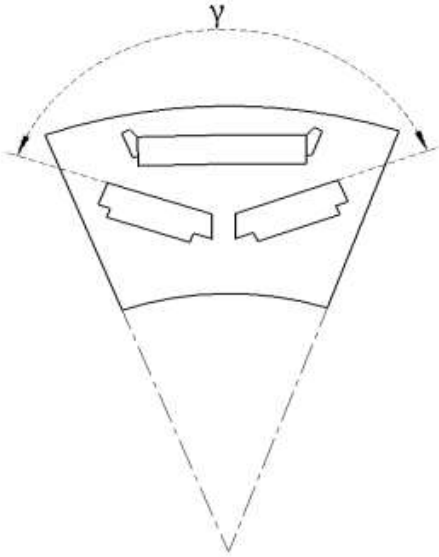

Fig 2.1: Angle between permanent magnets placed in the rotor of Internal Permanent Magnet motor

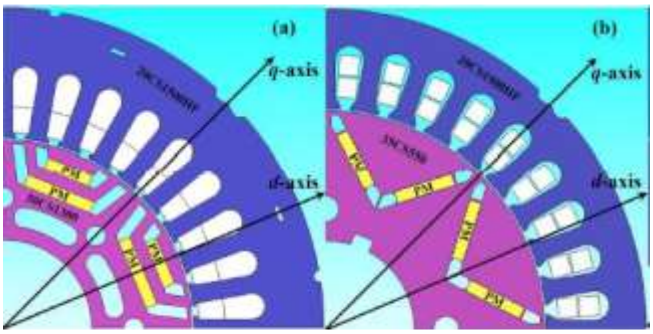

Fig 2.2: a) Double-layers interior permanent magnet synchronous machines (IPMSM). (b) V-shaped Internal Permanent Magnet Synchronous Motor

Ying Xie, Yu Xia, Zhi Wei Li and Fei Li et al. [4]. As a result, we are able to decrease the amount of motor vibration that is brought on by the radial force. The strategy that was utilised in this article brings about a reduction in the radial electromagnetic force, which in turn brings about a reduction in the variation of the torque. It has been discovered that motor vibrations can be caused by a variety of variables, including electromagnetic vibrations, mechanical vibrations, and rotor vibrations; however, only electromagnetic vibrations will be discussed in this particular piece of research. The design of the motor with an eccentric tooth edge is what is suggested in this study as a way to lessen the amount of vibration and noise produced by the motor. And finally, the results of comparing the air-gap flux density and torque ripple values before and after optimisation are shown. The observation was made that the average torque is approximately the same, but the ripple in the torque is reduced by nearly 30–40% of the prior value.

An improved version of an internal permanent magnet motor is proposed by Konstantinos I. Laskaris and Antonios G. Kladas et al. [5].. In order to examine the topology of the IPM motor, a 2D finite element model is utilised. Tooth width and magnet width are the two primary characteristics that are responsible for the effects that have on magnetic flux density. The geometry parameters of the magnets and the stator teeth, such as the magnet width (Wm), magnet length (Lm), and tooth width (Wi), which are depicted in figure 2.3, are changed in such a way that the highest possible torque is obtained.

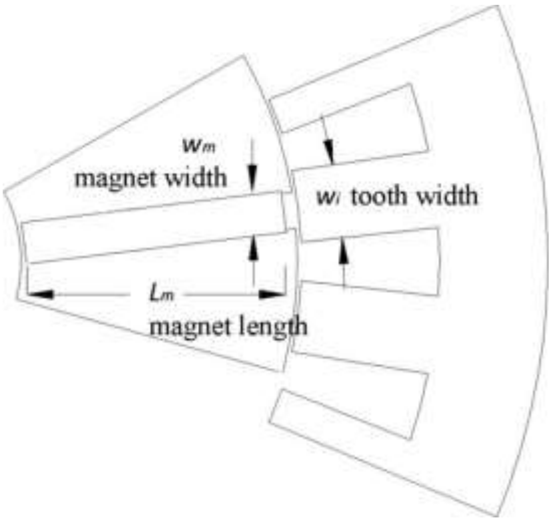

Fig 2.3: Geometry optimization parameters of IPMM

Motor innovation is dependent on the reduction of stator leakage, which is accomplished via the use of open stator slot geometries. Additionally, high efficiency in the frequent working speed range is accomplished by the utilisation of appropriate permanent magnet sizing and rotor arrangement.

Another design for a motor part has been investigated in this study, which is based on a comparative analysis of rotor poles and stator slots with varying numbers. In this research, Tae-Kyoung Bang, Kyung-Hun Shin, and Jeong-In Lee et al. [6] study two different combinations of models in order to acquire torque and torque ripple characteristics. These models are combined in two different ways. One with the 8-poles and 9-slots and other with the 8-poles and 12-slots.

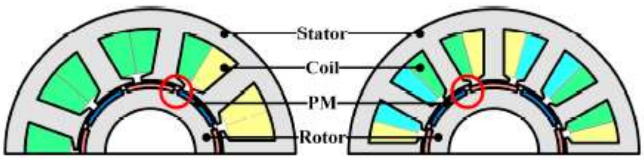

Fig 2.4: Electromagnet Analysis model for different number of slots present in Stator

Using ANSYS EM, an analytical model of permanent magnet synchronous machines with two alternative slot combinations was created and analysed.

Cogging torque, torque ripple, back EMF, and distortion features are investigated by a simulation, and plots are displayed so as to evaluate the aforementioned features of various stator slots that have 9 poles and 12 poles. It was determined that the 9-slot version had a distortion of 2.5 um, while the 12-slot model had a distortion of 0.04 um. Table 2.1 displays the results of a comparison between the 9 slots model and the 12 slots model.

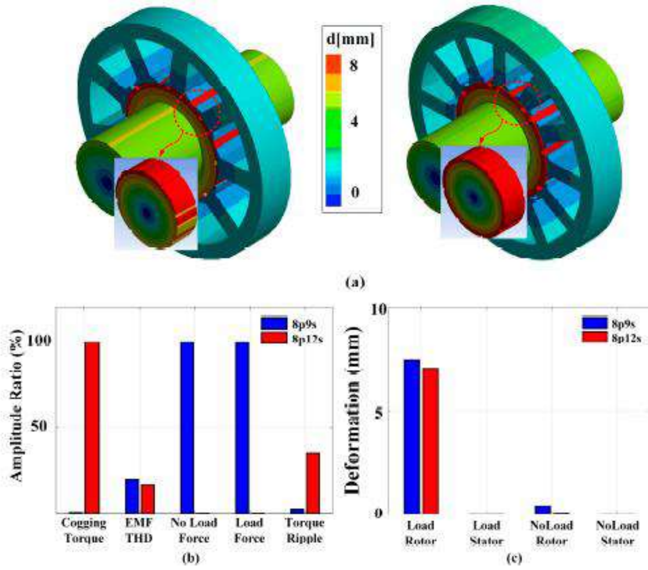

Figure 2.5: The analysis models of PMM

Table 2.1: Comparison of 9 and 12 slots

Sr. No.	Parameter	9-slot	12-Slot
1	Back-EMF THD	20.10%	16.77%
2	Cogging torque	1.53 mNm	311.53 mNm
3	Torque ripple	2.53%	34.80%
4	No-load EMF	8.85 N	0.01 N
5	On-load EMF	72.42 N	0.08 N
6	Deformations	2.5 um	0.04 um

Sources of vibrations are back-EMF, cogging torque, torque ripple, and UMF at the center of air gap. Both torque pulsation and maximum power factor (MPF) worked well for the 9-slot model, however back-EMF and ultimate maximum force (UMF) worked well for the 12-slot variant

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III SOFTWARE ANALYSIS

EFFECT OF VARYING AIR-GAP LENGTH:

Because it creates unwanted vibrations and acoustic disturbances in the motor, torque pulsing is one of the most critical design considerations in Permanent Magnet Motors. This is because torque pulsation causes the motor to overheat. The reduction of ripple in the torque output can primarily be achieved through either one of two approaches: either control techniques, which may include the current profiling method, or the optimal design method. Both of these methods are discussed more below. From a design point of view, we are going to investigate the procedure that is currently being followed. The optimisation of designs can also be accomplished through the application of a wide variety of techniques. Some of these techniques include skewing either the rotor or the stator, optimising the magnet's form and skewing, combining the appropriate amount of slots and poles, optimising the rotor shape, and optimising the uneven air-gap length.

The primary goal of optimising the air-gap length is to minimise torque ripple by ensuring that the flux density is evenly distributed across the rotor surface in a profile that is smoother. This is accomplished by maintaining a constant torque density. Therefore, we have studied air-gap profile optimization method so that not only torque ripple is reduced but also average torque and overall motor performance is improved. This air-gap length refers to the space that exists between the tip of the stator teeth and the permanent magnets on the rotor. For the purpose of research, we are going to choose a variety of air gap lengths to use as a criterion for monitoring torque characteristics and determining the ideal air gap length that can be achieved for the motor. When it comes to motors, the airgap length should range anywhere from 0.5mm to 1.2mm; if it goes beyond or below these limitations, the motor's performance will not be as efficient.

Now we will be observing torque characteristics for the motor with different airgap viz. 0.5mm, 0.7mm and 0.9mm. and parameters of the motor chosen are as given in below table 3.1.

Table 3.1: Motor parameters and dimensioning

Parameter		Parameter	
Rated Power (w)	1500	Stator O.D.	132mm
Rated speed	2000 RPM	Stator I.D.	68.4mm
Rated current	8 A	Rotor Type	Surface mounted
No. of rotor poles	4	Magnet thickness	3.5mm
No. of stator poles	24	Magnet span	70 degrees
Winding type	Single layer	Shaft Diameter	32mm
Airgap	(0.5,0.7,0.9) mm	Rotor O.D.	67mm

Now 2D Design of motor is prepared in RMxpert of Ansys Electronics with the given dimensions of the motor.

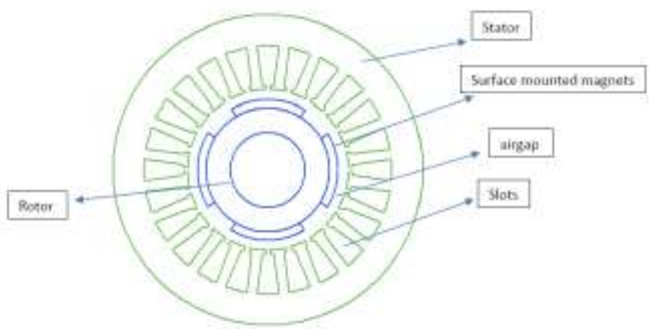

Figure 3.1: Airgap and other parts of permanent magnet motor

Design of slot is also made in RMxprt by selecting appropriate tooth type of the selected motor. Slot dimensioning is given in the table 3.2 below

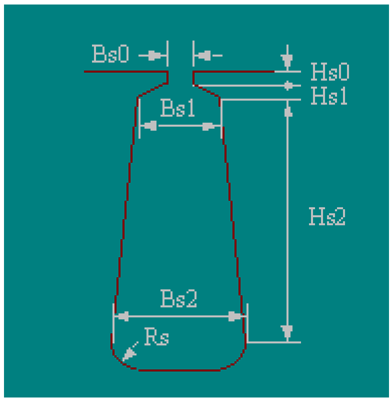

Fig 3.2: Slot dimensioning parameters

Table 3.2: Dimensions of the slot

PARAMETER	DIMENSION
HS0	0.5mm
HS1	1mm
HS2	8.2mm
BSO	2.5mm
BS1	5.6mm
BS2	7.6mm

When we calculate these values RMxprt generates a graph which gives cogging torque on one axis according to the different degrees while rotation. And torque value is getting calculated in the software. For 0.5mm airgap below graph is obtained.

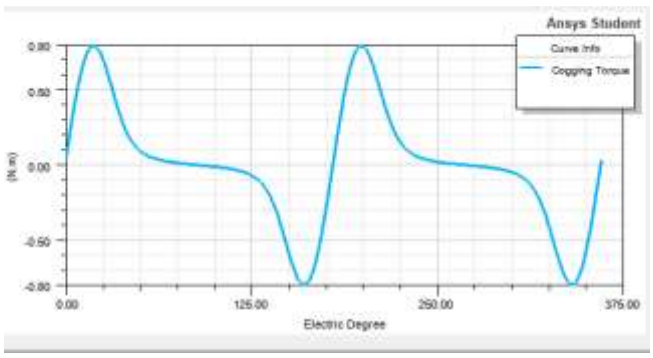

Fig 3.3: Cogging torque vs electric degree for 0.5mm airgap length

Maximum value for cogging torque is obtained as 0.7927 Nm. And torque value for this gap is 16.21 Nm. Also, for a given airgap maximum speed is calculated and for this airgap it is 884 RPM.
Now for 0.7mm airgap rotor dimensions are modified in a design way that the given gap is maintained. When calculated following graph is obtained as show in fig 3.4.

Maximum value for cogging torque is obtained as 0.6595 Nm. Torque value obtained for this gap is 15.76 Nm. And maximum speed is calculated for this airgap is 909 RPM.
Now in the end modifications are made in order to maintain the airgap of 0.9mm. Following graph of cogging torque is obtained associated with this airgap.

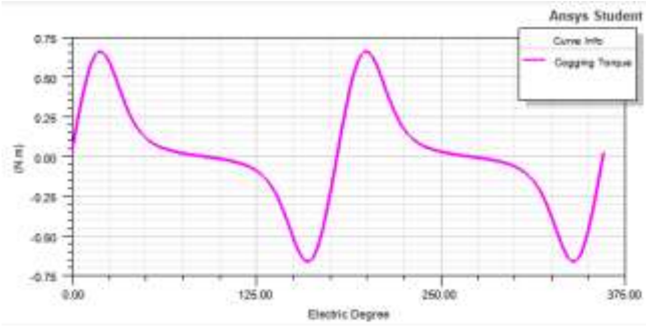

Fig 3.4: cogging torque vs electric degree for 0.7mm airgap length

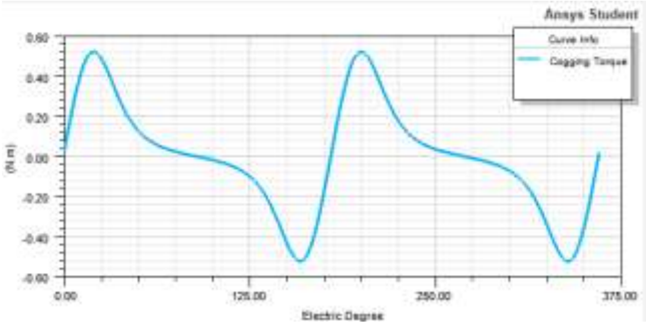

Fig 3.5: cogging torque vs electric degree for 0.9mm airgap length

Maximum value for cogging torque is obtained as 0.5205 Nm. Torque value obtained for this gap is 15.33 Nm. And maximum speed is calculated for this airgap is 935 RPM.

RESULTS:

Here we have obtained different value of cogging torque, rated torque, and speed according to the different air gap lengths present between stator and rotor from Ansys Electronics. These values are put up into the below table 3.3 for comparison.

Table 3.3: Torque, cogging torque, and speed values for different air-gap lengths

Sr. No.	Air-Gap length (mm)	0.5	0.7	0.9
1	Cogging torque (Nm)	0.7927	0.6595	0.5205
2	Torque (Nm)	16.21	15.76	15.33
3	Speed (RPM)	884	909	935

IV CONCLUSION

1. From results we observe that at the minimum air-gap length of 0.5mm torque produced is maximum as compared to other air-gap lengths but at the same time cogging torque produced is also maximum which will cause more torque ripple. And speed is relatively less.
2. At maximum air-gap length of 0.9mm less torque is produced comparatively and at the same time cogging torque produced is also less. Less cogging torque means operation of the motor will comparatively smoother.
3. Therefore, based on the requirement if high torque value is required minimum air-gap length ca be chosen and if smooth operation is desired then high air-gap length should be chosen. But looking for more practical purpose moderate air-gap length should be chosen taking torque and torque ripple into consideration.

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