A REVIEW ON DESIGN OPTIMIZATION TECHNIQUES OF PERMANENT MAGNET SYNCHRONOUS MOTOR

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***Abstract*— Now a days Electric Vehicles (EV) are getting more popular as they offer several advantages over conventional internal combustion engines, especially in terms of lower local emissions, higher energy efficiency, and decreased dependency upon oil. A motor in an electric vehicle provides the necessary force for the propulsion of a vehicle, which makes it the heart of electric vehicles**

There are different kinds of motors used in EV such as Induction motor, Brushless DC motor (BLDC), Permanent Magnet Synchronous Motor (PMSM), Switch Reluctance Motor. PMSM is developed in a greater way because new magnetic and earth materials are emerged to a greater extent. Among various kinds of motors employed for electric vehicle application, PMSM exhibits best performance because of its characteristics such as high-power density, high efficiency, lower mass, and lower moment of inertia.

This report will focus on construction of PMSM, different components used in PMSM. How different factors are affecting torque and other characteristics. Also design optimization techniques used for smoother operation of the motor by reducing the torque ripple. And experiment in Ansys Electronics is performed in order to observe motor performance by using air-gap design optimization technique.

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. High power and high efficiency are two key advantages of Permanent Magnet Motors. Motor that delivers high torque, power compaction, and exceptionally high efficiency in the same operation area are highly desirable. 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. The electromagnetic performance to be assessed includes maximum motor torque output for vehicle acceleration and the flux weakening capability for wide operating range under current and voltage limits. Motor performance is dependent on flux density produced by the magnets and thereby torque generated in the motor.

There are two types of Permanent magnet motors, those are 1) Internal Permanent Magnet Motor and 2) Surface mounted Permanent Magnet Motor. Magnetic Components geometry of Internal Permanent Magnet Motor is given below in Fig 1.

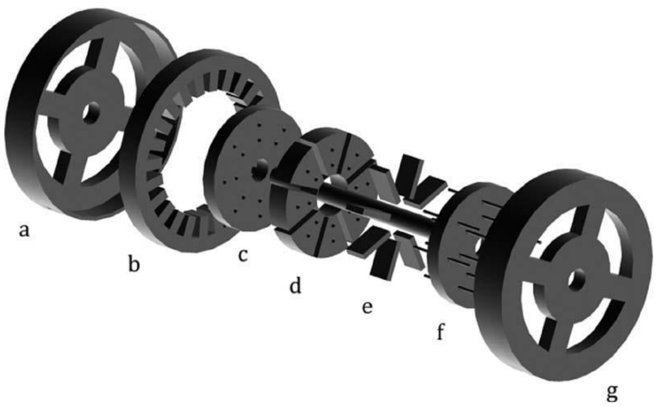

Fig 1.1: Magnetic components of IPM motor

Rotor magnetic circuit consists of eight laminated silicon steel boxes (Fig 1.1. d) and eight pieces of embedded permanent magnet (Fig 1.1. e). The stator (Fig 1.1 b) of the motor consists of stack of laminated non-orientated grain silicon steel which minimizes the core loss. There are 24 slots present in this stator and 3 phase distributed windings are arranged inside the stator slots. 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 (fig 1.1 f) made up of non-magnetic material hold the rotor rigid and which avoid strong eddy currents that would appear on the cast aluminium stands (Fig 1.1 a and g).

Efficiency of the motor is generally dependent on the torque produced, torque ripple, Back-EMF value, cogging torque, etc. Cogging torque is the torque needed to overcome the opposing torque created by the magnetic attractive force between magnets on the rotor and teeth of the stator. Cogging torque is an undesirable component for the operation of such a motor. It is especially prominent at lower speeds, with the symptom of jerkiness. Cogging torque results in torque as well as speed ripple; however, at high speed the motor moment of inertia filters out the effect of cogging torque. Torque ripple in motor is also one of the undesirable characteristics. It is the periodic increase or decrease in output torque as the motor shaft rotates. Torque ripple causes uneven and jerky motion in the motor. To understand necessary modifications made in motor design to reduce torque ripple and produce uniform electromagnetic force which will provide maximum torque output, we must understand design of the motor.

Parameters which affect the torque and other characteristics are Number of stator slots and rotor poles, Airgap length, Magnet sizing, Rotor structure, etc. Different designs of motors are studied based on these parameters and Ansys Electronics software is used for simulation purpose of the same. And through this Torque, torque ripple and cogging torque, etc. values are studied, and best design is used in order to achieve required outputs in efficient 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.

Khalid G. Mohammed et al. [1] performed investigational tests for the motor of an electric vehicle are shown for 3 different speeds, AC line-to-line voltages are measured, and instantly the current is drawn by the electric lines. Based on these currents and voltages, power input and power output values of the 3-phase synchronous motor are calculated in theoretical manner using the performance equations. Required torque and speed is calculated with the help of these tests.

Jinlong Zhang, Dejun Yin et al. [2] proposed improved design of permanent magnet synchronous motor by selecting angle between permanent magnets of the motor. Design of the angle γ between permanent magnets is studied. Magnet angles are kept between 96° to 136° as shown in below Fig 2.1

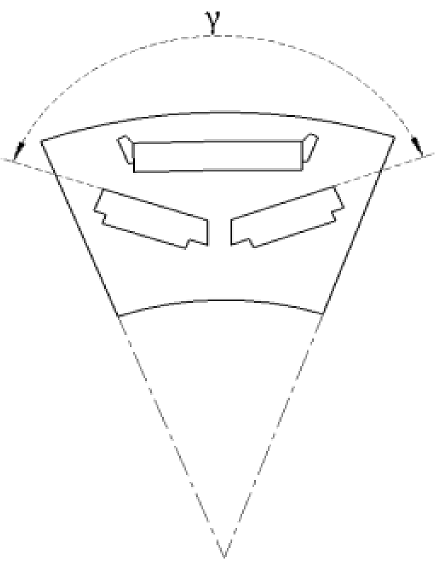

Fig 2.1: Angle between permanent magnets placed in the rotor of Internal Permanent Magnet motor

It is observed from simulation that when the angle is 96° air-gap flux density is small and results in leakage in flux densities of permanent magnets. And when angle is greater than 116° magnetic field is dispersed and magnetic flux leakage increases. When angle is kept 106°, output torque is maximum and air-gap flux density amplitude also increases. Therefore 106° angle is chosen for magnets and according to this simulation results are calculated. After improved design maximum output torque is 182.31 Nm, pulsating torque is 6.75 Nm and torque ripple is 3.7% of average peak torque. Focus is done on improving flux density and reducing the torque ripple of the motor.

Thanh Anh Huynh and Min-Fu Hsieh et al. [3] investigated the characteristics of IPMSMs and PM-SynRM in terms of electromagnetic and thermal performance via driving cycles for EV applications. Different types of permanent magnets are used inside the rotor to analyse electromagnetic performance through which maximum torque output for acceleration is assessed. Fig 2.2 shows design of permanent magnets used to analyze electromagnetic torque characteristics of the Internal Permanent Magnet Motor.

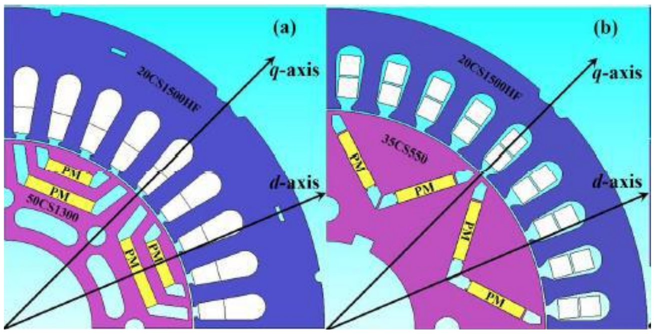

Fig 2.2: a) Double-layers interior permanent magnet synchronous machines (IPMSM). (b) V-shaped Internal Permanent Magnet Synchronous Motor

V-shaped IPMSM has advantage of flux weakening capability. Efficiency graph is plotted for both type of motors performing FEA and by experimental testing. It was observed that IPMSMs possess the benefit of high PM flux linkage, low armature current, and current angle to reach the maximum torque. Also, it is observed by comparison that in V-shaped IPMSM efficiency is more stable and better compared to double layer IPMSM.

Ying Xie, Yu Xia, Zhi Wei Li and Fei Li et al. [4] Proposed an unconventional stator tip arc shape to reduce the unevenness of the radial magnetic density distribution at the stator tip in this paper, thereby reducing the motor vibration caused by the radial force. The method used in this paper reduces the radial electromagnetic force and effectively reduces the torque fluctuation. Various factors resulting in motor vibrations are found such as electromagnetic vibrations, mechanical vibrations, and rotor vibrations, out of these electromagnetic vibrations were taken into consideration in this paper. In order to reduce the vibration and the noise of the motor, the eccentric tooth edge design is proposed in this paper. And results of air-gap flux density and torque ripple values are compared before and after optimization. It was observed that average torque is almost similar, but torque ripple is reduced by nearly 30%-40% of the previous one.

Konstantinos I. Laskaris, and Antonios G. Kladas et al. [5] proposes an enhanced internal permanent magnet motor that delivers high torque, power compaction, and exceptionally high efficiency in the same operation area. The proposed motor originality relies on the reduced stator leakage by adopting open stator slot geometries while achieving high efficiency in the frequent operating speed range through appropriate permanent magnet sizing and rotor configuration. 2D finite element model is used to analyse the topology of IPM motor. Tooth width and magnet width are the two main parameters because of which magnetic flux density is affecting. Geometry parameters of magnets and stator teeth such as magnet width (Wm), magnet length (Lm), tooth width (Wi) shown in figure 2.3, are modified in such a way that highest torque is obtained.

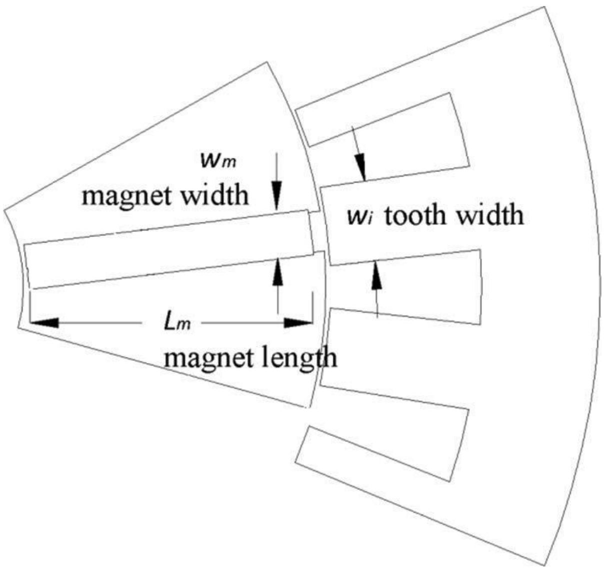

Fig 2.3: Geometry optimization parameters of IPMM

Motor originality relies on the reduced stator leakage by adopting open stator slot geometries while achieving high efficiency in the frequent operating speed range through appropriate permanent magnet sizing and rotor configuration.

Another design for motor part is studied in the which is based on comparative study for different number of rotor poles and stator slots. Two different combinations of models are studied by **Tae-Kyoung Bang, Kyung-Hun Shin, Jeong-In Lee et al.** [6] in this paper for obtaining torque and torque ripple characteristics. One with the 8-poles and 9-slots and other with the 8-poles and 12-slots.

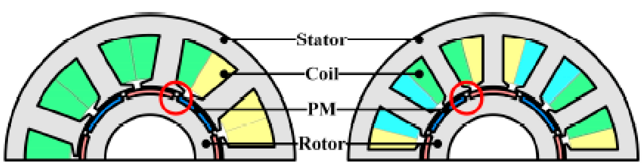

Fig 2.4: Electromagnet Analysis model for different number of slots present in Stator

The analysis model of permanent magnet synchronous machines with two different slot combination is performed using ANSYS EM software.

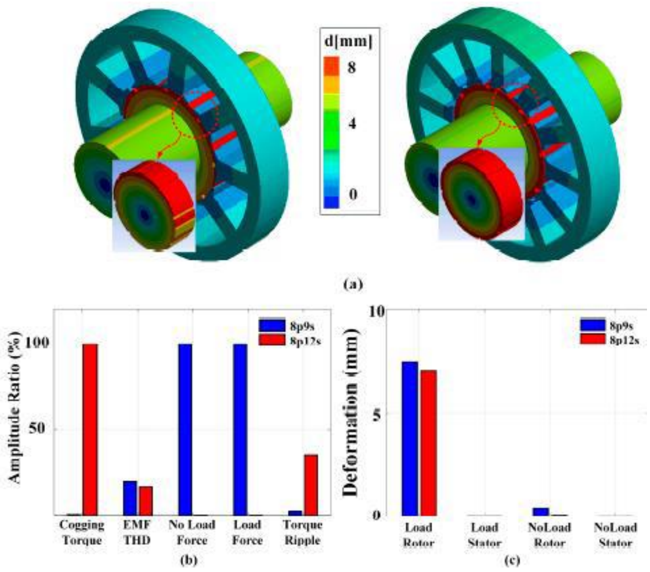

Figure 2.5: The analysis model of permanent magnet machines with two different pole/slot combinations: (a) electromagnetic analysis model and (b,c) prototype

Cogging torque, torque ripple, back EMF, deformation characteristics are studied through the simulation and graphs are plotted in order to compare these characteristics of different stator slots with 9 poles and 12 poles. Deformation for 9-slot: 2.5 um and deformation for 12-slot model is found out to be 0.04 um. Comparative results for 9 slots and 12 slots model are shown in table 2.1.

Table 2.1: Comparison of results of PMSMs according to the 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. Torque pulsation and MPF were effective for the 9-slot model, and back-EMF and UMF were effective for the 12-slot model.

III SOFTWARE ANALYSIS

EFFECT OF VARYING AIR-GAP LENGTH:

Torque pulsation is one of the most important design considerations in Permanent Magnet Motors, because it causes undesirable vibrations and acoustic noises in the motor. There are mainly two methods namely control techniques such as current profiling method and optimal design method which are used for this torque ripple minimization. We will look method which is used in design point of view. In design optimization also there are many techniques such as, rotor or stator skewing, magnet skewing and shape optimization, slot/pole number combinations, rotor shape optimization and unequal air-gap length optimization.

Main purpose of air-gap length optimization is distributing flux density on the rotor surface with a smoother profile by keeping the torque density constant in order to reduce torque ripple. 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 is the airgap between the rotor permanent magnets and tip of the stator teeth. For study we will be selecting different air gap length as a criterion for observing torque characteristics and finding out the best possible airgap length for the motor. For motor, airgap length should vary between 0.5mm to 1.2mm, beyond these limits performance of the motor is not so 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.

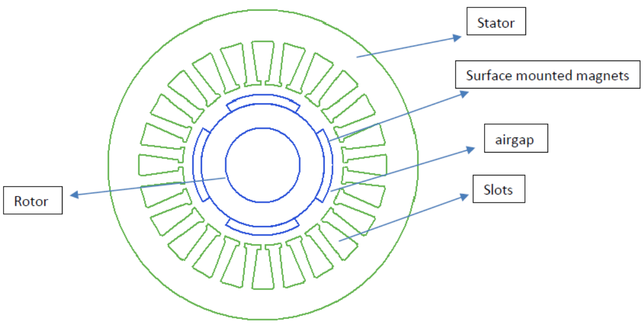

Figure 3.1: Airgap and other parts of permanent magnet motor

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

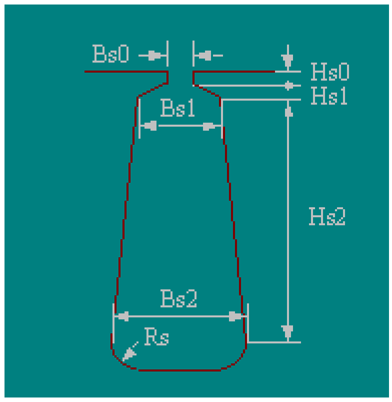

Fig 3.2: Slot dimensioning parameters

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.

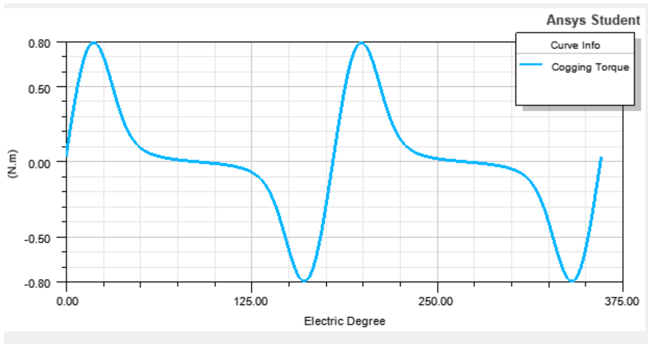

Fig 3.3: Cogging torque vs electric degree for 0.5mm airgap length

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.

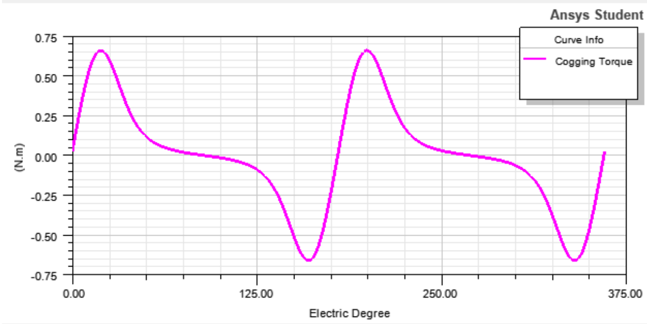

Fig 3.4: cogging torque vs electric degree for 0.7mm airgap length

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.

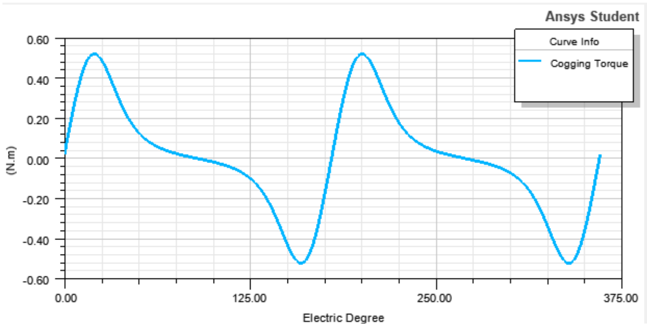

Fig 3.5: cogging torque vs electric degree for 0.9mm airgap length

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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