Outer Permanent Magnet Motor for Small EV

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Abstract

In this paper, a type of Outer permanent magnet (PM) motor designs is proposed for E scooter application as spindle motors. An existing permanent magnet motor has maximum speed of 50km/h with an electric motor 5kW-5000 rpm. In order to improve high speed operation, a higher speed electric motor 5.5 kW and 7000 rpm can run up to 70km/h. An Outer Permanent Magnet (PM) motor alternatives are designed and optimized in detail with optimal magnetic segment shape. The electromagnetic results of PM V shape motors are compared with the reference Outer U shape Permanent Magnet (SPM) motor for the same design requirements. Detailed loss analysis is also performed for the desired motor structure at high speeds. A prototype motor is manufactured, and initial experimental tests are performed. Detailed comparison between Finite Element Analysis and test data are also presented. It is shown that it is possible to have an optimized PM motor for such high-speed spindle application. This paper will figure out optimal angle of magnetic V shape for maximum torque and minimum torque ripple.

Abbreviation

PM	Outer Permanent Magnet
SPM	Outer U shape Permanent Motor

1. Introduction

Permanent magnet (PM) synchronous motors are quite popular in many applications due to their distinctive benefits such as high efficiency, high torque density, smaller size, and relatively low current requirements [1-3]. They also have low vibration, and low acoustic noise levels compared to other types of electric motors [4-7]. It is also possible to obtain high torque quality in PM motors both at low and high speeds. Such issue is quite critical especially for high performance application such as servo motors, spindle motors and direct drive applications. There exist various methods in order to obtain high torque quality in PM motors [1-7]. These methods include design modifications both at rotor and stator sides such as using different slot/pole combinations, skewing rotor or stator, magnet grouping, adding auxiliary slots and so on.

This paper focuses on the development of an PM spindle motor for E Scooter applications. A FEA analyses are performed, and some parametric optimizations are realized to achieve better torque quality and performance. Comparison of the designed spindle motors with respect to the reference SPM motor are also provided. Prototype motor is manufactured, and experimental tests are performed. It is shown that it is possible to have an improved PM motor for such spindle application.

2 PM design

In order to calculate rotor diameter and Slot length of PM, an analytical equation can solve and give the result, the most important factor are L/D ratio and torque density must be estimated in optimal range.

$$T=\frac{\pi}{4}\cdot D^2 L_{stk}.TRV \qquad (1)$$

Where,

D: outter rotor
Lstk: slot length
TRV=15-:-25 kNm/m3

The program is divided into three main parts: analytical calculation, exporting drawing and magnetic simulation. There are also some supporting parts including material library which also associate with FEMM library.

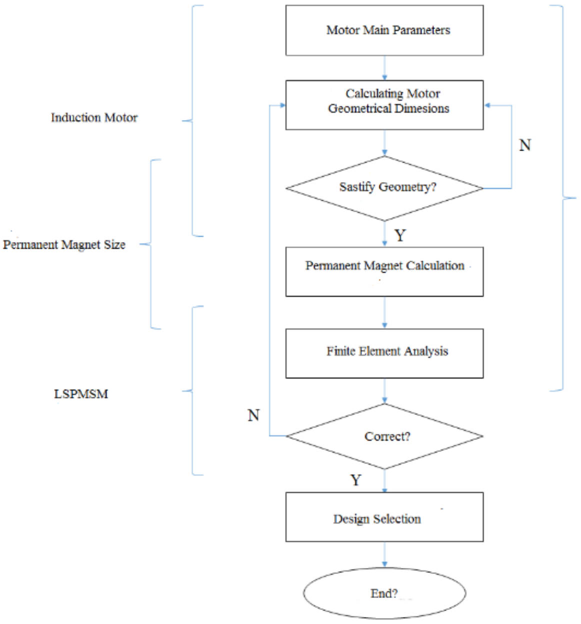


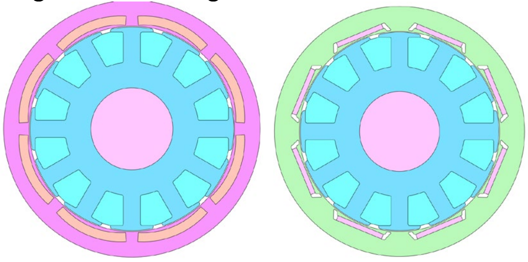
Figure 1. Program Structure

In this study, a OPM 5 kW- 3000rpm Outer U shape mounted PM motor is used as a reference motor. Firstly, initial sizing of the motor is carried out. Electromagnetic analyses are performed for the reference motor and then two different PM rotor designs are realized. U type PM motor design alternatives are investigated in detail using FEA and several parametric optimizations are also performed before finalizing the design. The PM and SPM motor specifications used in this study are given in Table I. Reference motor is an integral slot motor with 36/4 slot/pole combinations.

Table 1. Motor specifications

No	Parameters	Value
1	Power (W)	5000
2	Speed (rpm)	0-7200
3	Stator (Slots)	36
4	Rotor (poles)	8
5	Rotor Outer Diameter (mm)	98
6	Stator Outer Diameter (mm)	150
7	Stack length (mm)	125

The layout of stator and rotor lamination is shown in Figure 2. The 36 stator slots, 8 magnetic poles and the concentrated winding double layers have been designed in below figure.

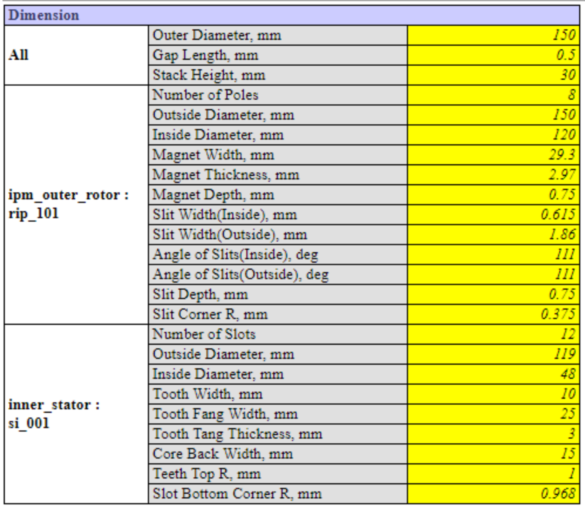


(a) C-shape (b) U shape

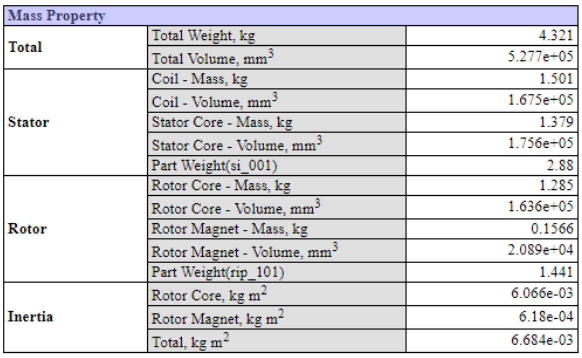
Figure 2. Rotor Design of Outer U shape Magnetic Motor

Electromagnetic material for stator, rotor and permanent magnetic have applied for this design as in table 2.

Table 2. PM Material



Dimension		
All	Outer Diameter, mm	*150*
	Gap Length, mm	*0.5*
	Stack Height, mm	*30*
ipm_outer_rotor : rip_101	Number of Poles	*8*
	Outside Diameter, mm	*150*
	Inside Diameter, mm	*120*
	Magnet Width, mm	*29.3*
	Magnet Thickness, mm	*2.97*
	Magnet Depth, mm	*0.75*
	Slit Width(Inside), mm	*0.615*
	Slit Width(Outside), mm	*1.86*
	Angle of Slits(Inside), deg	*111*
	Angle of Slits(Outside), deg	*111*
	Slit Depth, mm	*0.75*
	Slit Corner R, mm	*0.375*
inner_stator : si_001	Number of Slots	*12*
	Outside Diameter, mm	*119*
	Inside Diameter, mm	*48*
	Tooth Width, mm	*10*
	Tooth Fang Width, mm	*25*
	Tooth Tang Thickness, mm	*3*
	Core Back Width, mm	*15*
	Teeth Top R, mm	*1*
	Slot Bottom Corner R, mm	*0.968*



Mass Property		
Total	Total Weight, kg	4.321
	Total Volume, mm^3	5.277e+05
Stator	Coil - Mass, kg	1.501
	Coil - Volume, mm^3	1.675e+05
	Stator Core - Mass, kg	1.379
	Stator Core - Volume, mm^3	1.756e+05
	Part Weight(si_001)	2.88
Rotor	Rotor Core - Mass, kg	1.285
	Rotor Core - Volume, mm^3	1.636e+05
	Rotor Magnet - Mass, kg	0.1566
	Rotor Magnet - Volume, mm^3	2.089e+04
	Part Weight(rip_101)	1.441
Inertia	Rotor Core, kg m^2	6.066e-03
	Rotor Magnet, kg m^2	6.18e-04
	Total, kg m^2	6.684e-03

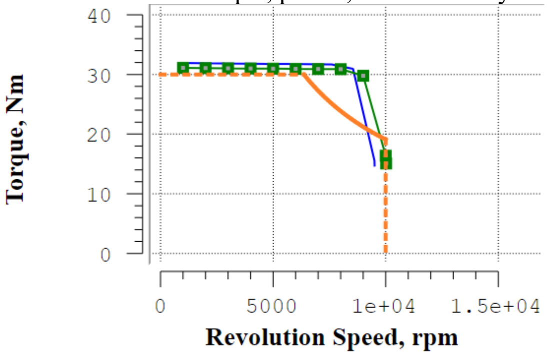
Figure 3 shows the magnetic flux density distribution at no-load condition, which shows flux density in air gap and in stator and rotor poles.

Table 2. Performance comparison

Parameters	PM	SPM	Unit
Average torque (virtual work)	24.014	24.985	Nm
Average torque (loop torque)	23.83	24.81	Nm
Torque Ripple (MsVw)	2.6991	1.098	Nm
Torque Ripple (MsVw) [%]	11.231	4.3998	%
Electromagnetic Power	5033.5	5226.5	Watts
Input Power	5259.3	5804.5	Watts
Output Power	4853.7	5086.9	Watts
Total Losses (on load)	405.63	717.58	Watts
System Efficiency	87.638	92.287	%
Shaft Torque	23.175	24.288	Nm

Average torque, output power, efficiency of SPM and PM are shown in table 2 at speed 2000. The Outer U shape magnetic mount structure is not robust at high speed due to radial forces. Efficiency of SPM is 87.6% and current density is 11 A/mm2 is quite high. So cooling method must be considered.

The stator and rotor dimensions are important for analytical model to calculate electromagnetic performance such as toque, power, and efficiency.



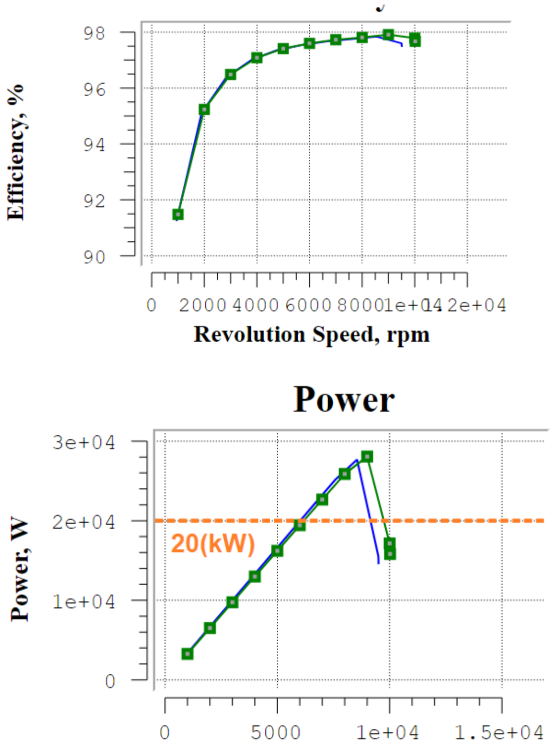


Figure 3. Torque, efficiency and power comparison

Figure 3 shows torque, efficiency and power comparison at maximum speed 10000 rpm. The torque ripple of the V shape PM prototype model is approximately 2% less than torque ripple results of the SPM model.

4. Experimental test results

The magnetic poles is manufactured and tested to validated torque performances. Rotor magnetic slots have manufacture by wire cutting after die-casting rotor bars and shaft assembly. The back-to-back test bench of DC generator and PM motor motor has setup as fig 15.

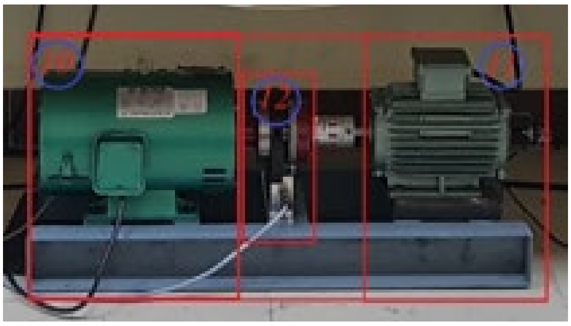


Figure 2. PM servo test bench

The whole hardware of torque and speed sensors was built together, and torque results are displayed in interface control. The torque and speed curves have been tested and measured in dynamic condition. The test result are good agreement with designed parameters.

The PM motor was setup to evaluate synchronizing speed under different load and voltage by auto run test system as flow IEC standard.

5. CONCLUSION

In this study, two different types of Outer permanent magnet motor designs are investigated for E Scooter. An existing SPM motor is used as a reference motor. Two different PM motor topologies are developed for the same application.

Extensive FEA analyses and parametric optimizations are performed, and results are compared with the reference SPM motor. PM motor is manufactured and tested since it has better torque quality and wider constant power region. Detailed comparison between FEA and test data are presented. It is seen that good agreement between the test data and FEA simulations are obtained. It is concluded that v-type PM motor has more benefits as opposed to SPM and conventional spoke type PM motor for such high speed milling applications.

6. REFERENCES

[1] T.M. Jahns and W. L: Soong, *"Pulsating Torque Minimization Techniques for Permanent Magnet AC Motor Drives-A review,"* IEEE Trans. Ind. Appl., vol. 43, no. 2, pp. 321-330, Apr. 1996.

[2] N. Bianchi and S. Bolognani, *"Design Techniques for Reducing the Cogging Torque in Outer U shape-Mounted PM Motors,"* IEEE Trans. Ind. Appl., vol. 38, no. 5, pp. 1259-1265, Sep./Oct. 2002.

[3] X. Ge, Z. Q. Zhu, G. Kemp, D. Moule and C. Williams, *"Optimal step-Skew Methods for Cogging Torque Reduction Accounting for Three-Dimensional Effect of Outer Permanent Magnet Machines,"* IEEE Trans. On Energy Conversion, vol. 32, no. 1, pp. 222-232, Mar. 2017.

[4] W. Q. Chu and Z. Q. Zhu, *"Investigation of Torque Ripples in Permanent Magnet Synchronous Machines with Skewing,"* IEEE Trans. On Magnetics, vol. 49, no.3, Mar. 2013.

[5] W. Q. Chu and Z. Q. Zhu, *"Reduction of On-Load Torque Ripples in Permanent Magnet Synchronous Machines by Improved Skewing,"* IEEE Trans. On Magnetics, vol. 49, no.7, pp. 3822- 3825, Jul. 2013.

[6] T. Li and G. Slemon, *"Reduction of Cogging Torque in Permanent Magnet Motors,"* IEEE Trans. On Magnetics, vol. 24, no.6, pp. 2901-2903, Jul. 2013.

[7] L. Dosiek and P. Pillay, *"Cogging Torque Reduction in Permanent Magnet Machines,"* IEEE Trans. Ind. Appl., vol. 43, no. 6, pp. 1565-1571, Now.-Dec., 2007.

[8] J. Urresty, J. Riba, L. Romeral and A. Garcia, *"A Simple 2-D FiniteElement Geometry for Analyzing Outer U shape-Mounted Synchronous Machines With Skew Rotor Magnets,"* IEEE Trans. On Magnetics, vol. 46, no.11, pp. 3948-3954, Nov. 2010.

[9] Z. Azar, Z.Q. Zhu and G. Ombach, *"Influence of Electric Loading and Magnetic Saturation on Cogging Torque, Back-EMF and Torque Ripple of PM Machines,"* IEEE Trans. On Magnetics, vol. 48, no. 10, pp. 2650-2658, Oct. 2012.

[10] R. Islam, I. Husain, A. Fardoun and K. McLaughlin*, "PermanentMagnet Synchronous Motor Magnet Designs With Skewing for Torque Ripple and Cogging Torque Reduction,"* IEEE Trans. Ind. Appl., vol. 45, no. 1, pp. 152-160, Jan./Feb. 2009.

[11] H. Chen, D. Dorrell and M. Tsai, *"Design and Operation of Outer Permanent-Magnet Motors with Two Axial Segments and High Rotor Saliency,"* IEEE Trans. On Magnetics, vol. 46, no. 9, pp. 3664-3674, Sep. 2010.

[12] C. Brecher, G. Spachthoz and F. Paepenmuller, *"Developments for High Performance Machine Tool Spindles",* Annals of the CIRP, pp. 395-399, 2007.