Torque imporvement of IPM motors with skewing magnetic designs

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ABSTRACT

In this paper, a type interior permanent magnet synchronous motor designs is proposed for sport scooter application to improve constant torque wide speed performance. Interior Permanent Magnet machines are widely used in automotive applications for their wide-speed range operation and low maintenance cost. An existing permanent magnet motor (commercial QS Motor) is 3 kW-3000 rpm. In order to improve torque and power in wide speed range, a IPM electric motor 5.5 kW-5000 rpm can run up to 100 km/h: An Step-Skewing Interior Permanent Magnet motor alternatives is designed and optimized in detail with optimal magnetic segment V shape. The electromagnetic charateristics of Interior Permanent Magnet motors with V shape are compared with the reference Surface Permanent Magnet motor for the same geometry parameter requirements. Detailed loss and efficiency result is also analyzed at rate and maximum 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 Interior Permanent Magnet motor for such high-speed traction application. This paper will figure out optimal angle of magnetic V shape for maximum torque and minimum torque ripple.

Keywords: Interior Permanent Magnet; Torque; V shape; Skewing design.

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 [4-8]. 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 [2-4, 6, 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 Interior Permanent Magnet (IPM) spindle motor for E Scooter applications. An IPM motor is designed with step-skewing and V shape of permanent magnet. A finite element analysis (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 Surface Permanent Magnet (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 IPM motor for such spindle application.

2. SPM AND IPM DESIGN

In order to calculate rotor diameter and Slot length of IPM, 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.

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

Where, D: Outter diameter rotor , L_{stk}: Stack length, TRV = 25 ÷ 35 kNm/m^3.

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.

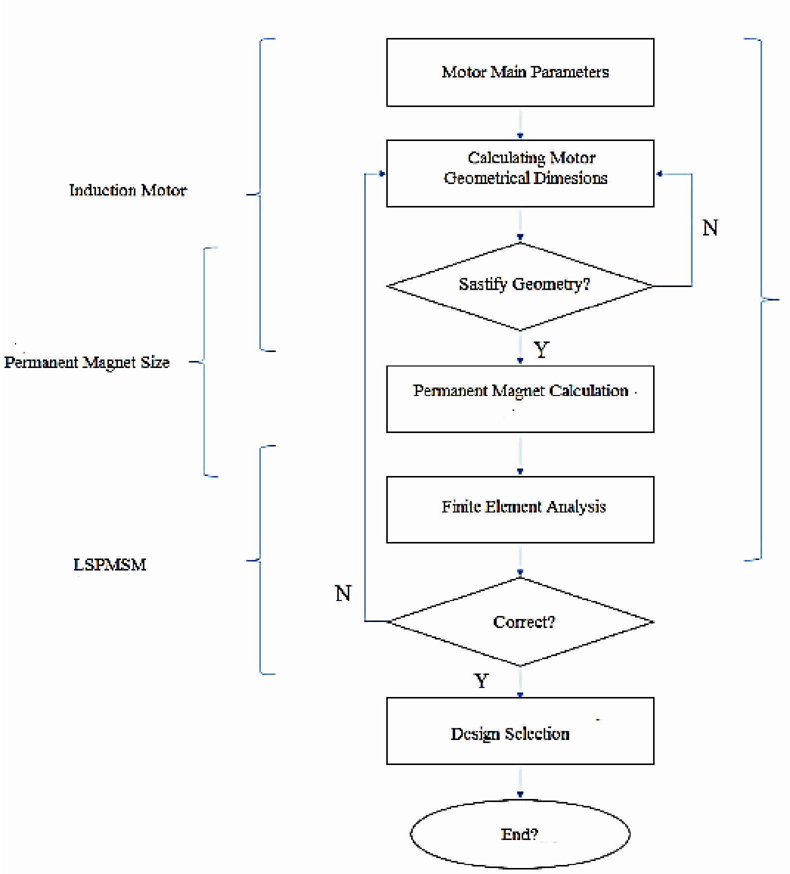

Figure 1. *Program Structure.*

Table 1. *Motor specifications.*

No	Parameters	Value
1	Power (W)	5000
2	Speed (rpm)	0 ÷ 5000
3	Stator (Slots)	36
4	Rotor (poles)	8
5	Rotor Outer Diameter (mm)	98
6	Stator Outer Diameter (mm)	150
7	Stack length (mm)	90

In this study, a SPM 5 kW-3000 rpm surface 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 IPM rotor designs are realized. I type IPM motor design alternatives are investigated in detail using FEA and several parametric optimizations are also performed before finalizing the design. The IPM and SPM motor specifications used in this study are given in table I. Reference motor is an integral slot motor with 36/8 slot/pole combinations.

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

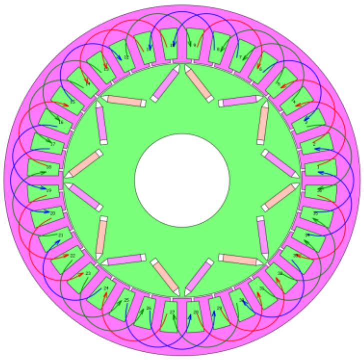

Figure 2. *Rotor Design of IPM.*

In order to minimize torque ripple, 4 step skewing rotor was designed in figure 3. The skewing angle is from -1.875 mechnical degrees to +1,875 mechnical degrees based on many steps running.

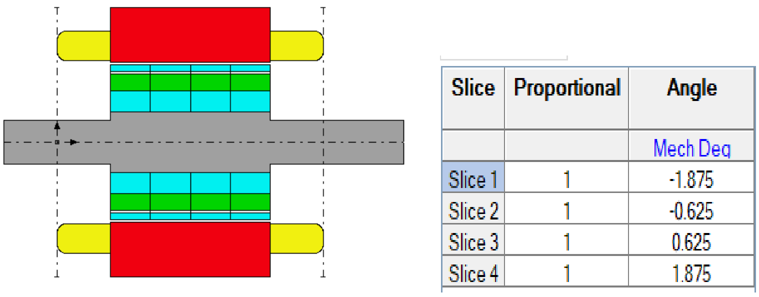

Figure 3. *Four Slices step-skewing rotor of IPM.*

Electromagnetic material for stator, rotor and permanent magnetic have applied for this design as in table 2. The IPM weight of magnet is lower 0.2 kg and the stator core and winding are keep the same.

Table 2. *IPM dimension parameters.*

No	*Parameters*	*Value*	*No*	*Parameter*	*Value*
1	Stack height (mm)	90	10	Number of magnets poles	8
2	Gap Length (mm)	0.5	11	Outside diameter rotor (mm)	100
3	Number of Slots stator	36	12	Inside diameter rotor (mm)	40
4	Outside diameter stator (mm)	150	13	Thickness of magnets (mm)	3
5	Inside diameter stator (mm)	101	14	Position of magnet (mm)	37
6	Tooth width stator (mm)	4	15	Width of magnets (mm)	14
7	Slot opening width stator (mm)	1	16	Angle of magnets	120^0
8	Core back width stator (mm)	9.8	17	Clearance between Magnets (mm)	3
9	Tooth tang depth stator (mm)	1,5		-	-

With optimal skewing angle, electromagnetic torque and efficiency performances have been evaluated in follow plotes. The torque and efficiency curves vs speed with skewed and non-skewed magnetic rotor are compared in fig 4.

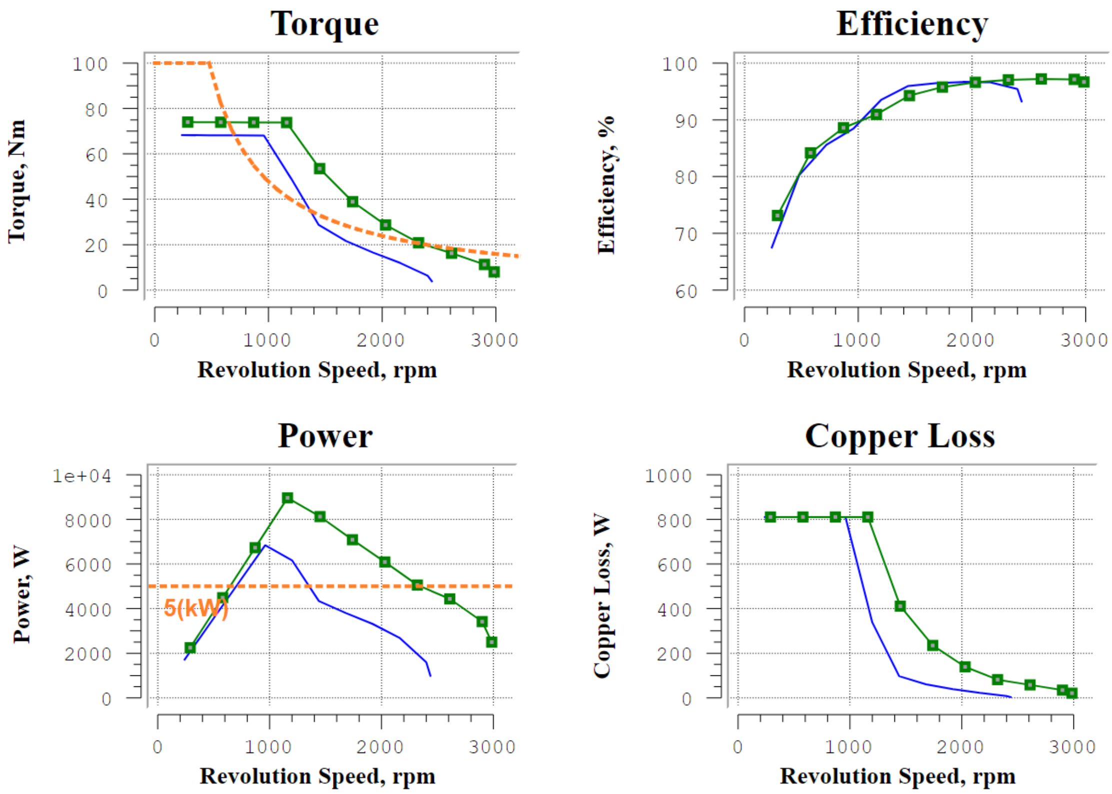

Figure 4. *Compare the torque, efficiency, power and copper loss of skewed and non-skewed magnetic rotor IPM.*

Table 3. *Performance comparison.*

Parameters	*IPM- Skewed*	*SPM-Non Skewed*	*Unit*
Average torque	24.014	24.985	Nm
Average torque	23.83	24.81	Nm
Torque Ripple	2.6991	1.098	Nm
Torque Ripple [%]	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	63.175	64.288	Nm

Average torque, output power, efficiency of IPM with are shown in table 3 at speed 3000 rpm. The surface 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.

Constant torque wide speed performances of IPM with skewed and non skewed magnet have calculated in figure 5. The torque-speed curves of IPM skewing is prolonged than the IPM -non skewd curves with limited current of 25A/72VDC because the back EMF waveforms is smaller and more sinusoidial.

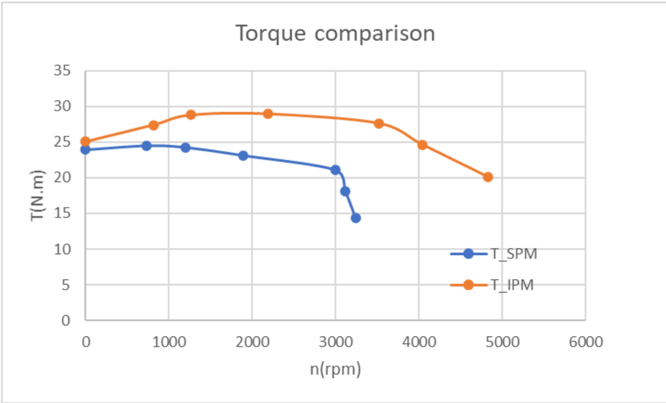

Figure 5. *IPM and SPM.*

Figure 6 shows back-EMFs at maximum speed 5000 rpm at no load as fig 2. Harmonic Distortion Back EMF Phase Voltage is 1.6%.

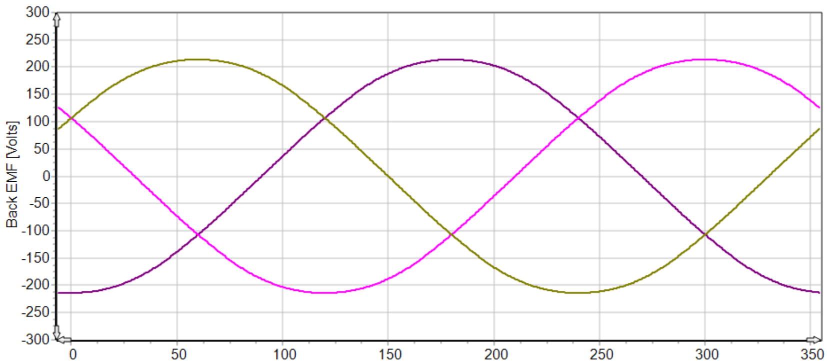

Figure 6. *Back EMF waveform.*

Figure 7 shows torque ripple waveform of 2.5% and average torque is 25 Nm at maximum speed 5000 rpm.

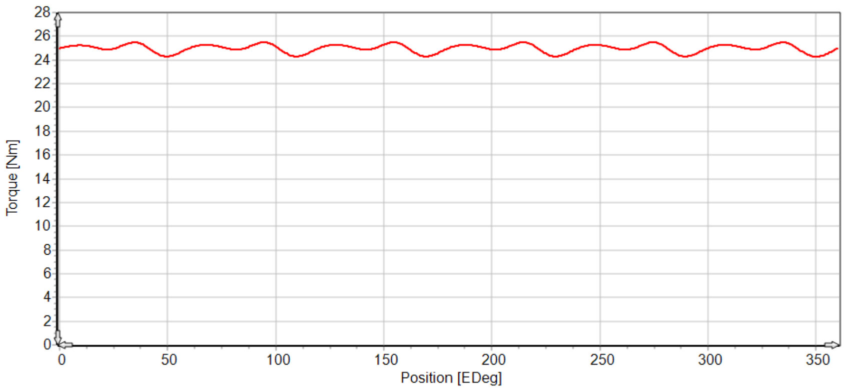

Figure 7. *Torque waveform versus electric angle.*

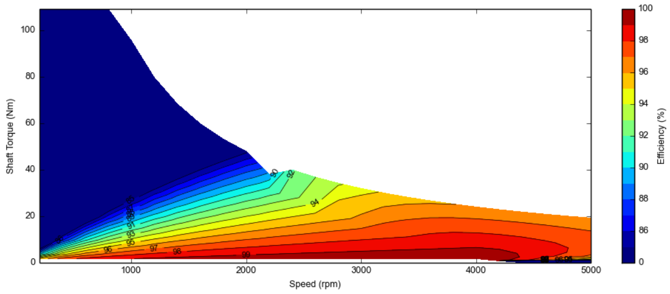

Figure 8. *Shaft torque versus electric angle and efficiency.*

The torque ripple of the V shape IPM prototype model is approximately 2% less than torque ripple results of the IPM model with 4 step-slice skewing. If increasing number of magnet segments, the torque ripples can be more reduced however the manufactures are facing some challenges in placing magnet pieces by machanical jig or frame.

An efficiency map of IPM proposal is plotted in peak torque and peak power modes with maximum DC current of 100 A and 72 VDC in figure 8. Maximum efficiency loop of 97% is possible achieve at high speed and low torque. This effect is from V shape magnet angle design.

3. IPM MANUFACTURED AND EXPERIMENTAL TEST IMPLEMENTATION

The rotor lamination and interrior magnet core were implemented by wire cutting and jig assembly in figure 9.

***Figure 9**. IPM rotor.*

The IPM V shape magnet is manufactured and tested to validated back EMF in no-load and average torque at maximum speed. Rotor lamination have manufacture by wire cutting before placing magnet and shaft assembly. The back-to-back test bench of DC generator and IPM 5 kW IPM motor has setup as figure 10.

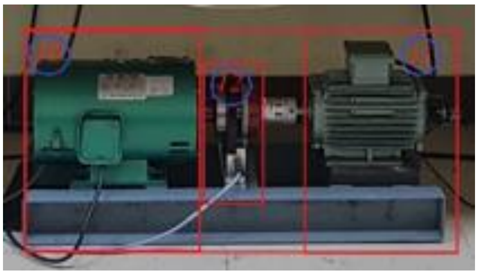

***Figure 10**. IPM motor test bench.*

The whole hardware of torque and speed sensors was built together, and torque results are displayed in interface control as figure 11.

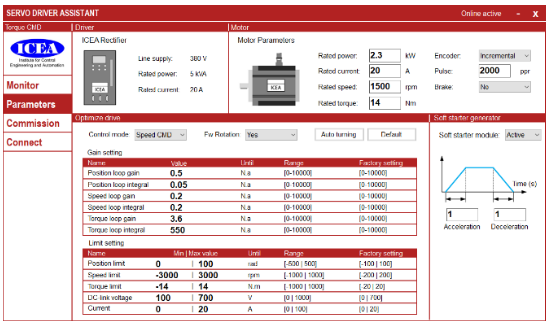

***Figure 11**. IPM motor control interface.*

The torque and speed curves have been tested and measured in dynamic condition with pre-setup speed and current. The maximum speed test result was implemented at 5000 rpm and average torque of 15 N.m as figure 12.

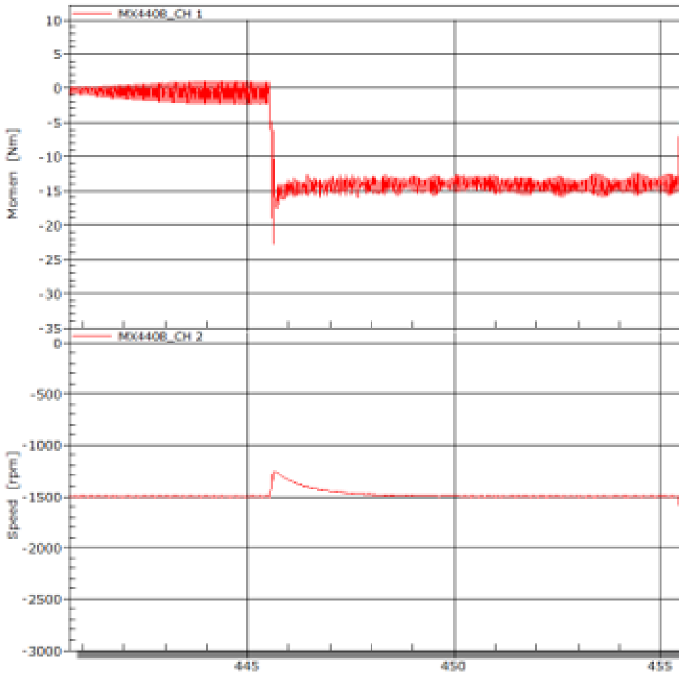

***Figure 12**. Torque and speed results.*

Full torque vs speed of the IPM motor under different load and voltage by auto run test system as EU drive cycle will be obtained by industrial lab and test bench.

4. CONCLUSION

In this study, two different types of interior permanent magnet motor and surface magnet moted designs are investigated for E sport Scooter. An existing SPM motor is used as a reference motor. Different V shape IPM 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. V-type IPM 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 IPM motor has more benefits as opposed to SPM and conventional spoke type IPM motor for such high speed E sport motorbycycle applications. The IPM motor is designed with step-skewing and V shape of permanent magnet at 5000 rpm and has average torque equal 15 N.m

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TÓM TẮT

CẢI THIỆN MÔ MEN ĐỘNG CƠ ĐỒNG BỘ NAM CHÂM VĨNH CỬU GẮN CHÌM VỚI NAM CHÂM RÃNH NGHIÊNG

Trong bài báo này, động cơ đồng bộ nam châm vĩnh cửu gắn chìm ứng dụng cho xe máy điện thể thao được thiết kế nhằm cải thiện khả năng mô men không đổi ở dải tốc độ cao. Động cơ đồng bộ nam châm vĩnh cửu gắn chìm được sử dụng rộng rãi trong ứng dụng cho ô tô nhờ khả năng giữ cho mô men không đổi ở tốc độ cao và chi phí bảo dưỡng thấp. Động cơ nam châm vĩnh cửu đã được thương mại hóa của hãng QS Motor có thông số kỹ thuật là 3 kW-3000 vòng/phút. Động cơ đồng bộ nam châm vĩnh cửu gắn chìm được thiết kế là 5,5 kW-5000 vòng/phút,có thể chạy tới 100 km/h bằng việc tối ưu góc sếp nam châm chữ V và ghép dạng chéo rãnh. Đặc tính điện từ của động cơ đồng bộ nam châm gắn chìm có nam châm chữ V được so sánh với động cơ đồng bộ nam châm gắn bề mặt khi có cùng một thông số kích thước hình học. Kết quả về hiệu suất và tổn hao sắt được phân tích ở dải tốc độ cực đại . Một mẫu động cơ nam châm vĩnh cửu theo thiết kế tối ưu đã được chế tạo và đo kiểm đánh giá. Kết quả phân tích theo phương pháp phân tích phần tử hữu hạn được so sánh với kết quả thử nghiệm. Kết quả thực nghiệm khẳng định sự tối ưu hóa của thiết kế động cơ nam châm vĩnh cửu ở dải tốc tộ cao. Bài báo cũng đã đưa ra góc sếp nam châm tối ưu là để tối đa mô men trung bình và tối thiểu mô men nhấp nhô.

Từ khóa: Động cơ đồng bộ nam châm vĩnh cửu; Mô men; Hình dạng chữ V; Thiết kế chéo rãnh.