ELECTROMAGNETIC CALCULATION AND DESIGN OF A 2.2kW INTERIOR PERMAGNENT MAGNET SYNCHRONOUS MOTOR WITH APPLICATION TO CNC MILLING MACHINE

TÍNH TOÁN VÀ THIẾT KẾ ĐIỆN TỪ ĐỘNG CƠ ĐỒNG BỘ NAM CHÂM VĨNH CỬU 2,2kW - ỨNG DỤNG CHO MÁY GIA CÔNG CNC

Dang Quoc Vuong*, Nguyen Quang Dich, Bui Minh Dinh

ABSTRACT

In this paper, a type interior permanent magnet motor designs is proposed for computer numerical control milling machine application as spindle motors. An existing surface mounted permanent magnet motor is used as a reference motor. The I type interior permanent magnet motor alternatives is designed and optimized in detail. The electromagnetic results of interior permanent magnet motors are compared with the reference surface permanent magnet motor for the same design requirements. The detailed loss analysis is also performed for the desired motor structure at high speeds. A prototype motor is manufactured and initial experimental tests are also performed. The 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 a high speed spindle application.

Keywords: *Interior permanent magnet motor - IPM, spindle motor for milling machine, I-type IPM, Finite element method - FEM.*

TÓM TẮT

Trong bài báo này, thiết kế động cơ nam châm vĩnh cửu gắn trong được đề xuất cho ứng dụng máy gia công điều khiển số máy tính như là động cơ trục chính. Một động cơ nam châm vĩnh cửu gắn trên bề mặt được sử dụng như một động cơ tham chiếu để so sánh kết quả. Động cơ nam châm vĩnh cửu kiểu I được thiết kế chi tiết và tối ưu hoá. Các kết quả điện từ của động cơ nam châm vĩnh cửu gắn trong được so sánh với động cơ nam châm vĩnh cửu tham chiếu gắn bề mặt với các yêu cầu thiết kế tương tự. Phân tích chi tiết tổn hao cũng được thực hiện cho cấu trúc động cơ ở tốc độ cao. Một động cơ mẫu được sản xuất và các thử nghiệm ban đầu cũng được thực hiện. So sánh chi tiết giữa phân tích phần tử hữu hạn và dữ liệu thử nghiệm cũng được trình bày. Điều đó cho thấy rằng một sự tối ưu hoá động cơ nam châm vĩnh cửu rotor gắn trọng được thiết kế và ứng cho máy gia công ở tốc độ cao.

Từ khóa: *Động cơ nam châm vĩnh cửu gắn trong, động cơ cho máy gia công, kiểu động cơ IPM kiểu I, phương pháp phần tử hữu hạn (FEM).*

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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 interior permanent magnet (IPM) spindle motor for computer numerical control (CNC) milling applications. A Finite element method (FEM) analyses are performed and some parametric optimizations are realized in order to achieve the better torque quality and performance. The comparison of the designed spindle motors with respect to the reference surface permanent magnet (SPM) motor is also provided. The 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. DESIGN AND FINITE ELEMENT MODELING OF SPM AND IPM MOTORS

In this paper, a 2.2kW, 3000rpm surface mounted PM motor is used as a reference motor. Firstly, an 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. The I type IPM motor design alternatives is investigated in detail using the FEM and several parametric optimizations are also performed before finalizing the design.

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2.1. Analysis of Reference SPM Motor

A reference SPM motor specifications used in this study are given in Table 1. The reference motor is an integral slot motor with 36/4 slot/pole combinations.

Table 1. SPM parameters

No	Parameters	Value
1	Power (W)	2200
2	Speed (rpm)	0 - 3000
3	Stator (Slots)	24
4	Rotor (poles)	4
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 1, with 24 stator slots and 4 magnetic poles, and the maximum speed is 3000rpm and 1500rpm for the normal speed. The current waveforms are the square shape because the surface magnetic mount is equal to air gap (Fig. 2). The efficiency of SPM is 88% and 5.22A/mm2 for the current density (Fig. 3). From two limits above, we can improve a new design of IPM to solve those problems. The electromagnetic torque is kept as a constant at 14N.m from zero to 1500rpm and down to 12N.m at 3000rpm. The power is from zero to maximum value of 3800W at seed of 300rpm (Fig. 4).

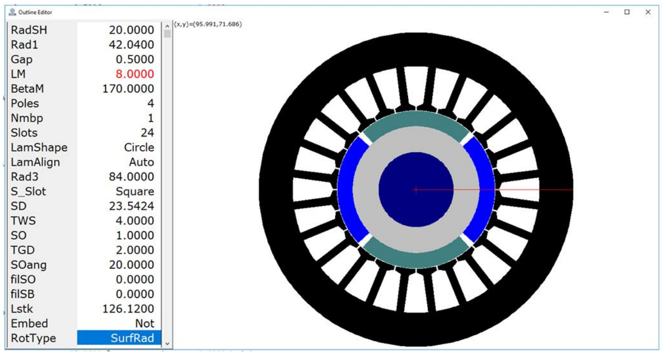

Figure 1. Stator and rotor lamination

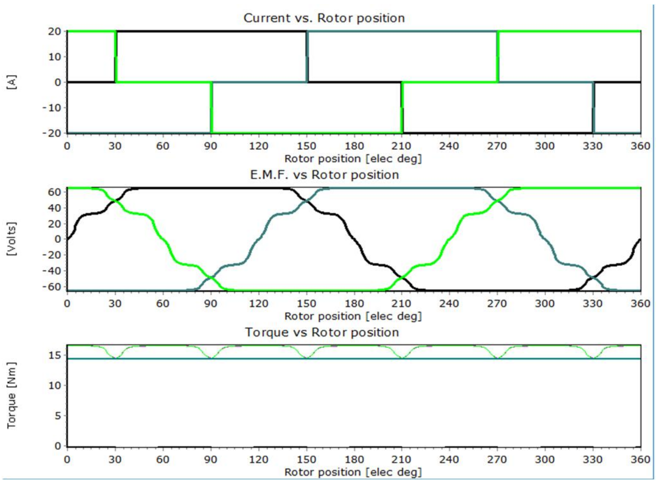

Figure 2. Current, EMF and Torque curves

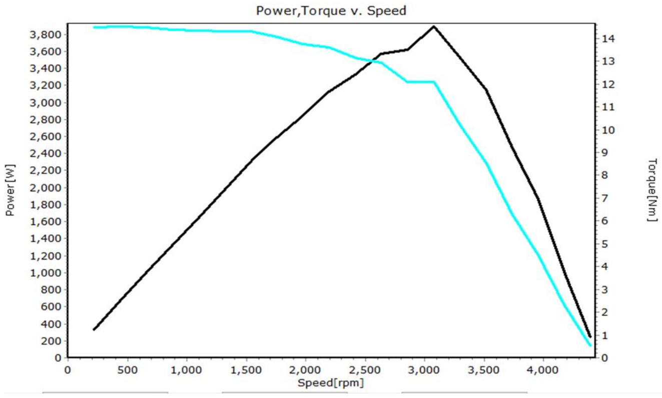

Figure 3. Power and torque and speed

2.2. IPM design

In order to calculate the rotor diameter and slot length of IPM, an analytical equation can be solved and given the result. The most important factor is L/D ratio and torque density must be estimated in the optimal range [8-12].

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

where D is the outer rotor dimension, L_{stk} is the slot length and TRV= 15÷25 kNm/m^3.

In order to design the IPM servo motor with low inertia moment, the L/D ratio is about from 1.4 to 1.6 [10], this means that the motor structure with the long stack length and the small outer rotor. It is easy to speed up and down or stop, the basic parameters of IPM 2,2kW motor is shown in Table 2.

Table 2. IPM parameters

No	Parameters	Value
1	Power (W)	2200
2	Speed (rpm)	0 - 3000
3	Stator (Slots)	36
4	Rotor (poles)	4
5	Rotor Outer Diameter (mm)	80
6	Stator Outer Diameter (mm)	132
7	Stack length (mm)	130

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

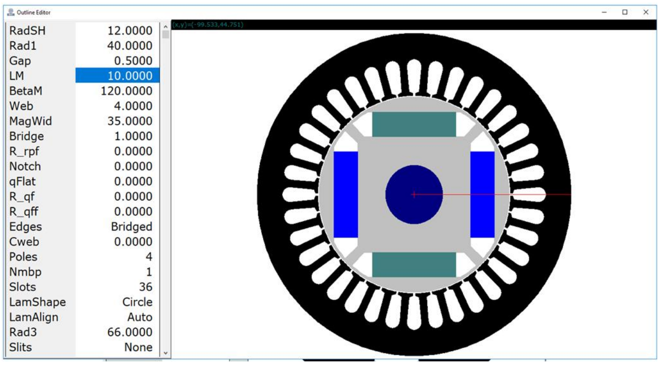

Figure 4. IPM Design of Stator and Rotor slots

The electromagnetic torque T_e and the currents (I_d and I_q) can be calculated vis the below equations, i.e,

$$T_e = mp(\psi_d I_q - \psi_q I_d), \quad (2)$$

$$\psi_d = \psi_{1Md} + L_d I_d,\ \psi_d = L_q I_q, \quad (3a\text{-}b)$$

$$T_e = mp[(\psi_{1Md} I_q + I_d I_q(L_d - L_q)], \quad (4)$$

$$I_d = -I\sin\gamma\,, I_d = I\cos\gamma. \quad (5a\text{-}b)$$

where I_d an I_q are respectively the direct axis and quadrature axis currents, ψ_d is the direct axis flux, ψ_{1Md} is the mutual direct axis flux, L_d is the direct axis inductance, L_q is the quadrature axis inductance and γ is the phase angle. The follow chart of calculation of IPM motor can be obtained in Figure 5.

The most important factors of the IPM motor design are ratios of E/U and X_q/X_d because they directly effect on the efficiency and maximum torque. Normally, The ratio of E/U is from 0.6 to 0.8 and from 3 to 6 for ratio of X_q/X_d. If ratio of X_q/X_d is close to 2, then the reluctance torque is small. But the ratio of X_q/X_d will reaches to 4, and the magnetic circuit is saturated. If the ratio of E/U is less than 1, then the IPM can work more in over flux or in saturation. The ratio of X_d/X_q will make in decision about reluctance torque, and the IPM has a big speed range being close to 4 values. The electromagnetic torque T_e is then defined as

$$T_e = mp[(\psi_{1Md} I_q + I_d I_q(L_d - L_q)]$$
$$= mp[(E_{q1} I_q + I_d I_q(X_d - X_q)]/\omega \quad (6)$$

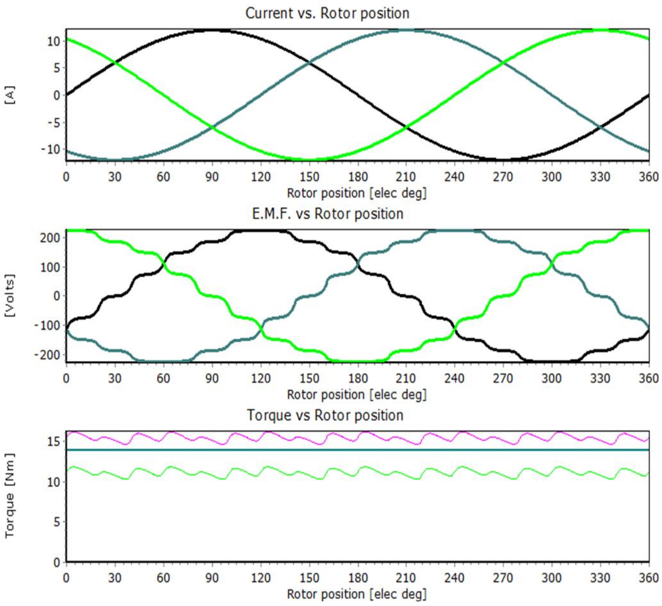

Figure 5. Current, EMF and Torque curves

An improved efficiency is 92.9% with torque of 14Nm and 1500rpm. The electromagnetic results of current, voltage and torque waveforms have been presented in Figure 5. The average torque is about 14Nm and torque ripple of 7%. The power and torque curves are shown in Figure 6 with maximum power of 4kW, and the average torque is down from 18Nm to 12Nm at the full speed being from 0 to 3500 rpm.

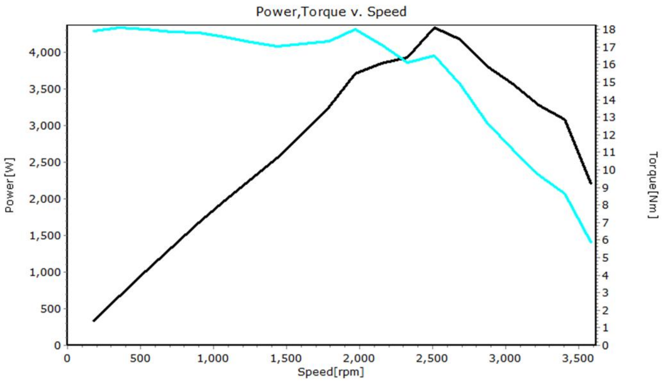

Figure 6. Power and torque and speed

3. EXPERIMENTAL TEST RESULTS

In order to test the IPM of 2,2kW in 4 quard, the test bench can be operated in 04 models as motoring and generating, forward and reverse. Because this motor will be used for the CNC application. Hence, it can stop in few second and is kept at average torque at the rating level (Figure 7).

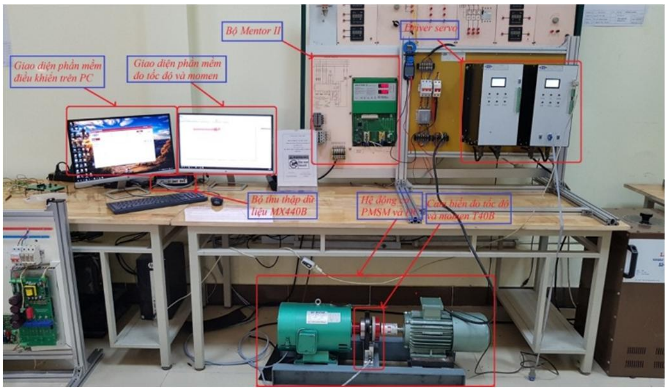

Figure 7. Full test bench system with maximum speed of 3000rpm

Rotor magnetic slots have been manufactured by wire cutting after die-casting rotor bars and shaft assembly. The back to back test bench of DC generator and the IPM motor of 2,2kW has setup (Figure 7). The whole hardware of torque and speed sensors is then built together and torque results are displayed in interface control (Figure 8). The designed motor is connected DC generator for testing in every model.

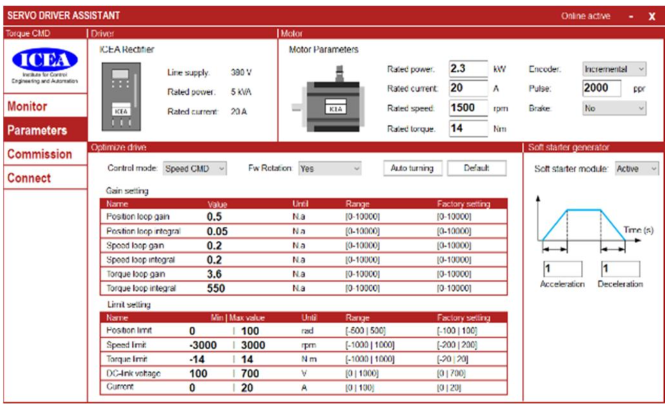

Figure 8. IPM servo motor control interface

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The torque and speed curves have been tested and measured in dynamic condition. The test results are good agreement with designed parameters (Figure 9). The IPM motor is setup to evaluate synchronizing speed under different load and voltage by auto run test system as flow IEC standard. All static and dynamic test result have saved in IEC result template depicted in Figure 10. Maximum efficiency is 89% at rated power and overload capacity is 125%, after comparing with design target, experimental results are full agreement and over IE2 class.

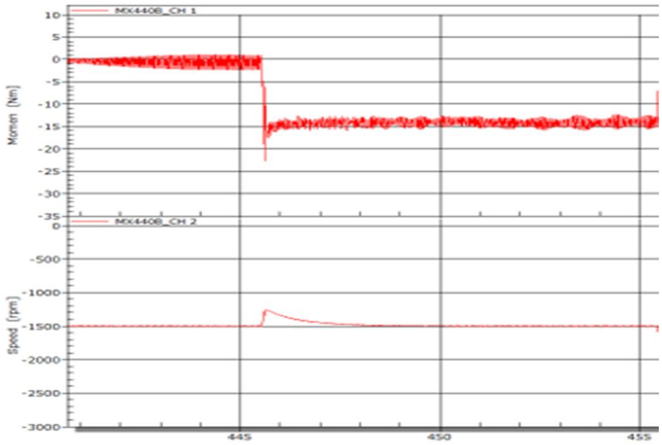

Figure 9. Torque and speed results

Date of test:		Report number:		Date of issue:	

Motor description				
Rated output power	kW	2.2	Manufacturer	BACHKHOA
Rated voltage	V	380	Model Nr.	BKHN
Rated current	A	0	Serial Nr.	
Rated speed	min^{-1}	1500	Duty type IEC 60034-1	
Supply frequency	Hz	50	Design	
Number of Poles	-	4	Insulation class IEC 60085	
IEC 60034-30-1 (rated)	IE-Code		Max. ambient temperature (°C)	

Initial motor conditions			
Test resistance	R_1	Ω	5.942
Winding temperature	θ_0	°C	26.3
Ambient temperature	θ_a	°C	24.1

6.1.3.2.1 Rated load test			
Test resistance	R_N	Ω	7.005
Winding temperature	θ_N	°C	52.8
Ambient temperature	θ_a	°C	23.9

6.1.3.2.3 Load curve test			Test resistance before load test			R	Ω	7.005
Rated output power		%	125 %	115 %	100 %	75 %	50 %	25 %
Torque	T	N.m	17.463	16.084	13.988	10.461	6.962	3.497
Input power	P_1	W	3134.61	2861.77	2470.44	1836.94	1230.7	653.31
Line current	I	A	4.908	4.451	3.826	2.858	1.976	1.342
Operating speed	n	min^{-1}	1498.8	1498.7	1499	1498.7	1499	1499
Teminal voltage	U	V	379.3	380.2	380.4	379.4	379.9	380.4
Frequency	f	Hz	50	50	50	50	50	50
Winding temperature	θ_w	°C	52.4	52.3	52.2	52.4	52.4	52.3
			Test resistance after load test			R	Ω	6.908

6.1.3.2.4 No-load test					Test resistance before no-load			R	Ω	6.908
Rated voltage		%	110 %	100 %	95 %	90 %	60 %	50 %	40 %	30 %
Input power	P_0	W	153.6	120.9	108.5	96.7	98.9	131.5	181.3	251.7
Line current	I_0	A	2.031	1.598	1.353	1.072	1.127	1.88	2.669	3.513
Terminal voltage	U_0	V	417.7	379.8	360.8	342.1	227.6	189.5	151.6	114.3
Frequency	f_0	Hz	50	50	50	50	50	50	50	50
W. temperature	θ_w	°C	52.7	52.5	52.2	52.1	51.9	51.8	51.4	51.4
					Test resistance after no-load test			R	Ω	6.682

6.1.3.3 Efficiency determination								
Rated output power corr.	$P_{2,I}$	%	125 %	115 %	100 %	75 %	50 %	25 %
Output power corrected	$P_{2,I}$	W	2740.8	2524.2	2195.8	1641.8	1092.8	548.9
Slip corrected	s, I	p.u.	0.01	0.02	0	0.02	0	0
Input power corrected	$P_{1,I}$	W	3134.6	2861.8	2470.4	1836.9	1230.7	653.3
Iron losses	P_{fe}	W	0.5	1	1.6	2.2	3	3.8
Frict. and wind. losses corr.	$P_{fw,I}$	W	82.1	82.1	82.1	82.1	82.1	82.1
Additional-load losses	P_{LL}	W	54.4	46.1	34.9	19.5	8.6	2.2
Stator losses corrected	$P_{s,I}$	W	253.1	208.2	153.8	85.9	41	18.9
Rotor losses corrected	$P_{r,I}$	W	2.4	2.3	1.5	1.5	0.8	0.4
Power factor	cos I	%	97.2	97.6	98	97.8	94.7	73.9
Efficiency	I	%	87.48	88.13	88.91	89.59	88.98	83.55

Figure 10. Experiment result template in Quatest I

4. CONCLUSION

In this study, two different types of interior permanent magnet motor designs are investigated for CNC milling machines as a spindle motor. An existing SPM motor is used as a reference motor. Two different IPM motor topologies are developed for the same application. The extensive FEA analyses and parametric optimizations are performed and results are compared with the reference SPM motor. The V-type IPM motor is manufactured and tested since it has better torque quality and wider constant power region. The detailed comparison between the FEA and the test data are presented. It is seen that a good agreement between the test data and FEA simulations are obtained. It is concluded that the V-type IPM motor has more benefits as opposed to SPM and conventional spoke type IPM motor for such high speed milling applications.

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THÔNG TIN TÁC GIẢ

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Viện Điện, Trường Đại học Bách khoa Hà Nội