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ELECTRIC MOTOR DESIGNS WITH SKEWING STRUCTURE TO MINIMIZE TORQUE RIPPLE

THIẾT KẾ ĐỘNG CƠ ĐIỆN VỚI KẾT CẤU CHÉO RÃNH STATOR NHẰM GIẢM MÔMEN ĐẬP MẠCH

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ABSTRACT

A permanent magnet brushless DC motor can be designed with different rotor configurations based on the arrangement of the permanent magnets. Rotor configurations strongly influence the performance of permanent magnet electrical motors. The aim of this paper is to compare and evaluate different rotor configurations for permanent magnet brushless DC motor with or without skewed stator slots. Nowadays, most of the DC motors are used with surface mounted permanent magnet rotors, because it is very easy to install and maintain. A finite element method has been applied to analyze and compare the different geometry parameters and configurations of motors. This paper focuses on the analysis of electromagnetic structure of two brushless DC motors with the same rated powers and dimensions of stator and rotor, with different number pole pairs and slots.

In this paper, the skewing slot is considered for the permanent surface mounted brushless DC motor for eliminating torque ripples. In order to observe the skewing stator effect, the stator lamination layers are skewed with different angles. With determined skewing angle, the cogging torque will theoretically reduce and the harmonic components of the flux density space are reduced, as well.

Keywords: *Permanent Magnetic Brushless DC motor, Finite Element Method, Ansys Maxwell, SPEED software, Magnetic flux density.*

TÓM TẮT

Động cơ một chiều nam châm vĩnh cửu không chổi than có thể được thiết kế với các cấu hình rôto khác nhau dựa trên sự sắp xếp của nam châm vĩnh cửu. Cấu hình của rotor ảnh hưởng rất lớn đến hiệu suất của động cơ điện nam châm vĩnh cửu. Mục đích của bài báo này là so sánh và đánh giá các cấu hình rôto khác nhau cho động cơ một chiều nam châm vĩnh cửu không chổi than có hoặc không có rãnh chéo. Ngày nay, hầu hết các động một chiều đều sử dụng rotor với nam châm vĩnh cữu gắn trên bề mặt, vì nó rất dễ dàng lắp đặt và bảo dưỡng. Bài báo đã áp dụng phương pháp phần tử hữu hạn để phân tích và so sánh sự khác nhau về tham số và kích thước hình học của động cơ. Bài báo tập trung vào phân tích cấu hình điện từ của hai động cơ một chiều không chổi than cùng công suất và cùng kích thước của stator và rotor, nhưng số cực từ và số rãnh khác nhau.

Trong bài báo này, rãnh chéo được áp dụng cho động cơ điện một chiều không chổi than với nam châm gắn bề mặt rotor để giảm mô men đập mạch. Để quan sát hiệu ứng rãnh chéo stator, các lá thép stator được cắt chéo với các góc nghiêng khác nhau. Với góc nghiêng đã được xác định, về mặt lý thuyết, mô-men đập mạch sẽ được giảm và thành phần sóng hài của mật độ từ cảm cũng được giảm theo.

Từ khóa: *Động cơ điện một chiều không chổi than, phương pháp phần tử hữu hạn, phần mềm Ansys Maxwell, phần mềm SPEED, mật độ từ cảm.*

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ABBREVIATION

FEM	Finite Element Method
LSPM	Line Start Permanent Magnet
BLDC	Brushless Direct Current
PM	Permanent Magnet

1. INTRODUCTION

The PMBLDC motors have been widely used in our life because of their attractive features like compactness, low weight, high efficiency, and ease in control [1, 2]. The reliability of the BLDC motor is high since it does not have any brushless to wear out and replace. The stator consists of stacked steel laminations with windings placed in the slots where as the rotor is made of PM that can varies from two to twelve pole pairs with alternate north and south poles.

Different rotor configurations are available for the PMBLDC motor namely surface mounted PM design with the interior or exterior rotors, the interior PM design with buried magnets etc., each having specific strengths and weaknesses [4]. Among these the radial-fluxes, the surface mounted type is commonly used for its simplicity formanu facturing and assembling. But this type of motors provides a low inductance value so that the overall time constant is reduced. This introduces a high torque ripple which is undesirable in servo applications. Therefore, another rotor design with PM embedded inside the rotor namely tangentially magnetized PM motors is considered. Performance evaluation of these two motors is discussed in this paper. The FEM has been applied to design BLDC motor widely in [3 - 5].

2. PMBLDC MOTOR ANALYSIS

The first analysis is considered for for a three phase BLDC motor of 35kW, for p = 12, Z = 36 (Figure 1). Magnet Vacodym 677HR is magnet material used due to its good thermal stability allowing its use inapplications exposed to high temperature about 180^{0}C. The flux density is selected about 0.8T.

$$\mu_0\mu_m = \frac{\Delta H}{\Delta B} \rightarrow \mu_m = \frac{\Delta H}{\mu_0 \Delta B} = \frac{1.18T}{915kA/m.\mu_0} = 1.026 \quad (1)$$

The geometry specifications of the motor used for the analysis are listed in Table 1.

Table 1. Geometry parameters of PMBLDC Motor

No	Parameters	Unit
1	Outer diameter	218 mm
2	Rotor diameter	116 mm
3	Slot length	112 mm
4	Normal Torque	200 Nm
5	Maximum Torque	750 Nm
6	Speed	3600 rpm

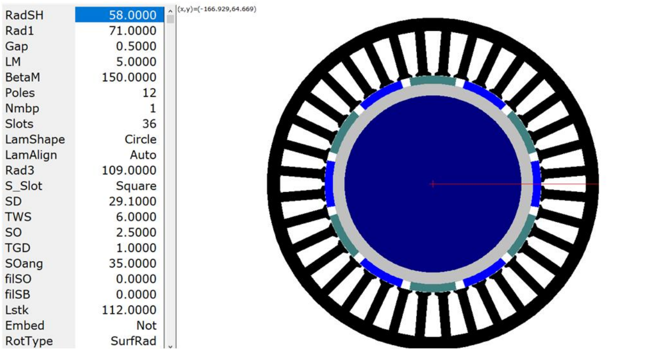

Figure 1. Model of a BLDC motor of 35kW (p = 12, Z = 36)

The design requirements are low cost, overload capacity, complex controller, efficiency and reliability. For electric vehicle applications, the manufacturing cost, complex controller are not so important, but the efficiency is the first priority of this design. With those requirements above, a layout of BLDC motor was calculated by SPEED software shown in Figure 1.

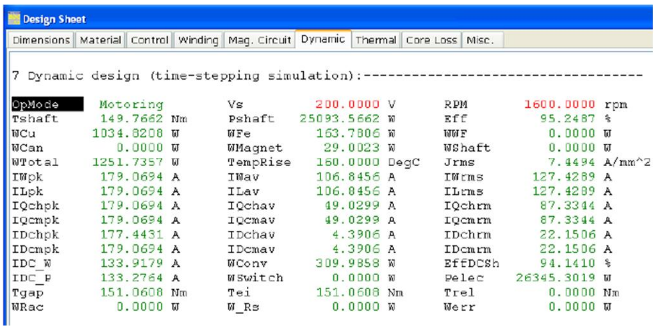

Figure 2. Performances of a BLDC Motor

Based on this design, some basic performances are shown in Figure 2. The most important parameter is efficiency of 95.2%. The efficiency is optimized by control angles from 0 to 12 degree. The torque on the shaft is 149.7Nm with 200V and 180A.

In order to evaluate the maximum torque of the motor, a maximum current is applied to determine when the permanent magnetic is irrecoverable. The maximum torque is 801Nm at speed of 660rpm with a current I = 959.4A and the efficiency is quite low about 66%. Other basic parameters are expressed in Figure 3.

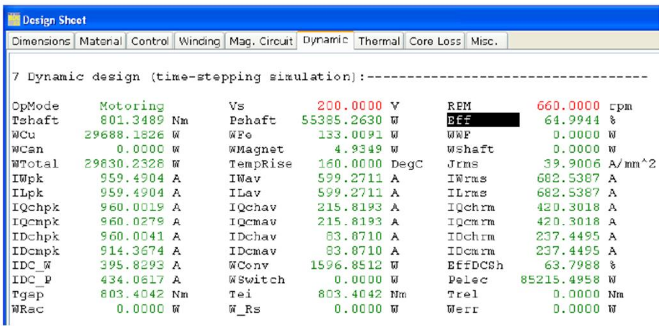

Figure 3. Maximum Torque Performances of a BLDC Motor

However, this design is still not yet optimal. To improve the design, different motor configurations, controlling angles can be adjusted to achieve maximum efficiency but the geometry parameters in Table I are kept constant.

3. PMBLDC DESIGNS BY THE FEM

The second analysis is considered for a three phase BLDC motor of 35kW, for p = 20, Z = 18 (Figure 4). In comparison with the one presented in Section 2, some basic parameters are now adjusted to get a maximum efficiency. The efficiency is calculated based on copper and iron losses. Those losses depend on stator and rotor teeth dimensions. The stator yokes are changed from 10 to 11mm and the controlling angle Th0 is considered from 20 to 40 degree. An optimal design with a maximum efficiency of 96.11% is shown in Figure 4. The slot factor is less than 0.5.

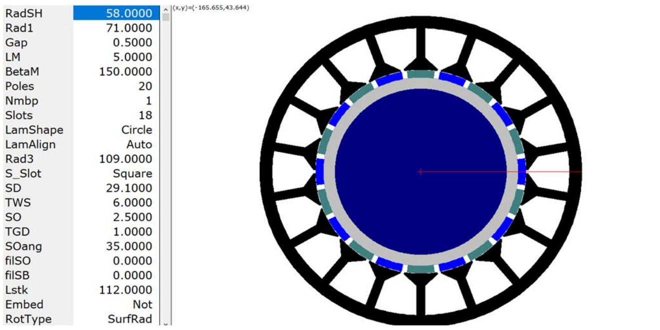

Figure 4. An optimal design of PMBLDC Motor p = 20, Z = 18

Some operation points have been recorded to monitor torque performances in Table 2. It is easy to know the maximum efficiency of 96.11% at speed of 1600rpm, and the shaft torque is 750 at speed of 200rpm with a lower efficiency of 39%. Turn on (Th0) and turn off (ThC) angles for the BLDC are important and optimal parameters. Those angles will influence to the efficiency and torque performances. They are defined by the magnetic angle T/2;

$$\frac{T}{2} = \frac{360p}{2xZ} : 2 = \frac{20x360}{3x2x18} : 2 = 33.33 \quad (2)$$

The Th0 has to adjust around the basic angle T/2 to get maximum torque if Th0 < T/2 and get the maximum efficiency if Th0 > T/2, the detail is given in Table 2.

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Table 2. Important operation points.

n (rpm)	T (Nm)	η (%)	I (A)	Th0 (°)	P_{cu} (W)	P_{fe} (W)
1600	108	96.11	156	38	139	558.1
800	150	92.1	200	20.5	58.3	1004.6
800	200	90.2	270	24	64.1	1758.4
200	750	39.2	1000	21.8	12.9	24564.26

A 2D BLDC motor model is simulated by the FEM software. After meshing the geometry model included magnetic, silicon steel and insolation materials, the electromagnetic characteristics have been obtained in Figure 5. The flux density distribution of rotor and stator is resulted at 800rpm and 270A.

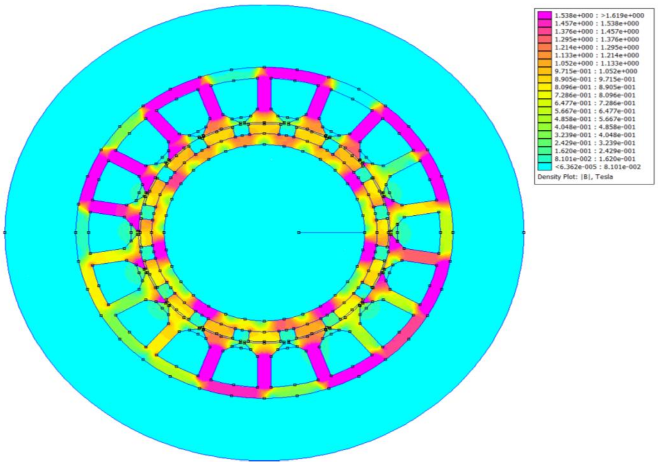

Figure 5. Flux density results

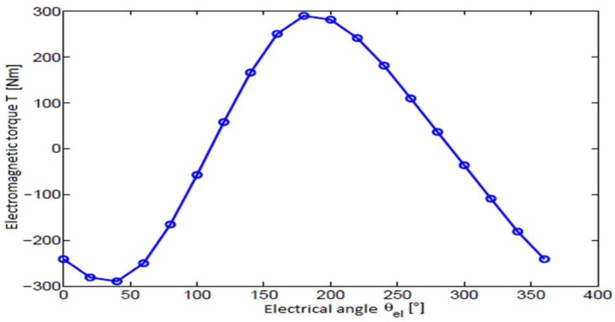

Figure 6. Electromagnetic torque curves with electric current I = 400A

Based on this simulation, the electromagnetic torque curves have also determined at different rotor positions being from 0 to 360 degree, with I = 400A (Figure 6). The flux density at the air gap has been investigated at different modes such as no-load, full load and 90, 180 degree shift (Figure 7). Many steps of rotor positions and currents, the torque and flux density results have recorded and saved in Matlab files to plot those characteristics. Electromagnetic forces are calculated at different speeds presented in Figure 8. The electromagnetic forces can be obtained by the analytical method via the equations:

$$e = -\frac{d\psi}{dt} = -\frac{d\psi}{dt}.\frac{d\theta}{dt} = -\frac{d\psi}{dt}.2\pi.n \approx -\frac{\Delta\psi}{\Delta\theta}.2\pi.n \qquad (3)$$

The flux linkage and inductance are implemented by the FEM simulation as results.

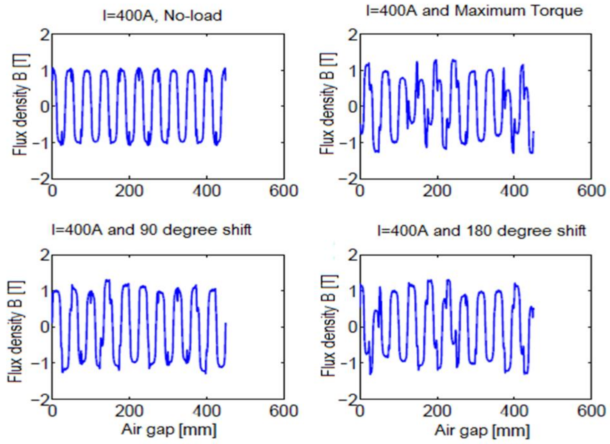

Figure 7. Flux density and air gap length curves with electric current I = 400A

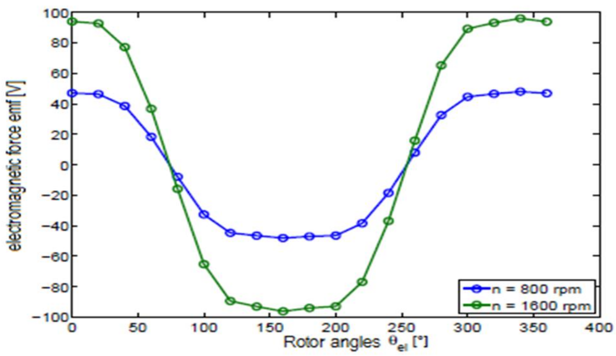

Figure 8. Electromagnetic forces and speeds

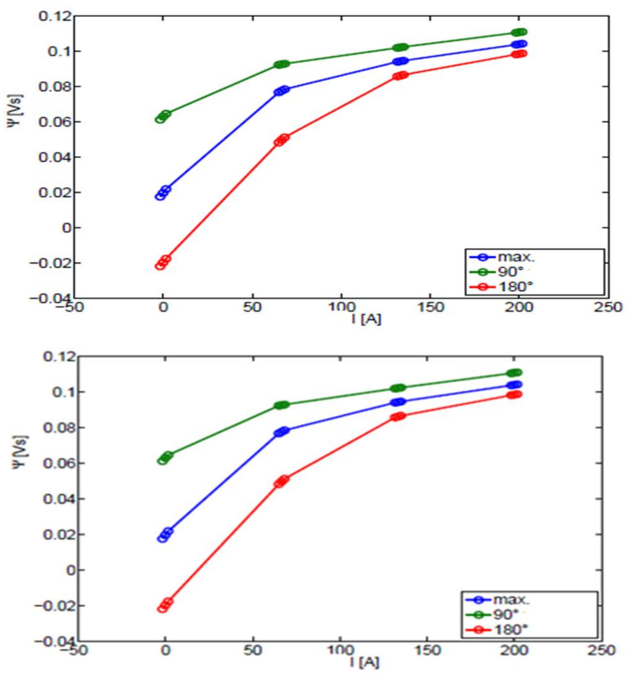

Figure 9. Flux linkage and current (left) and Inductance curves and rotor angles (right)

The inductance can be inferred from flux linkage curves as equation:

$$dL = \frac{d\psi}{di} \approx \frac{\Delta\psi}{\Delta i} \qquad (4)$$

4. SKEW ANGLE CALCULATION

The skewing method is used frequently in BLDC motors for eliminating this cogging torque. With the optimum skew angle, the cogging torque can be eliminated theoretically. Skewed slots for the stator lamination layers are illustrated in Figure 10. Any consecutive slots are numbered as 1 and 2 to show the beginning position for the first layer. Depending on optimum skew angle, each layer should be skewed one by one.

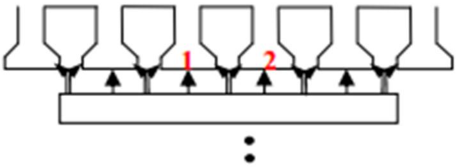

Figure 10. Cogging torque analysis.

5. APPLICATION PROBLEM

The cogging torque can be calculated from stored energy in the air gap. Variation of the co-energy gives the cogging torque [6]:

$$T_c = \frac{dW}{d\theta}, \quad (5)$$

where T_c is the cogging torque, $d\theta$ is the displacement with mechanical degree, and dW is the stored co-energy in the air gap.

The cogging torque is periodic along the air gap. By using this periodicity feature, Fourier series of the cogging torque can be obtained [7]:

$$T_{skew}(\theta) = \sum_{i=1}^{\infty} K_{sk}.T_i.\sin(iC_p\theta_m + \theta_i), \quad (6)$$

where K_{sk} is the skew factor which is 1 for non-skewed motor laminations. C_p is least common multiple between the number of pole and number of stator slots, T_i is absolute values of the harmonics, θ_m is the mechanical angle between stator and rotor axis while motor is rotating and represent to the phase angle K_{sk}, that is skew factor, the defined by:

$$K_{sk} = \frac{\mathrm{Sin}(\frac{iC\pi\alpha_{sk}}{N_S})}{iC\pi\alpha_{sk}/N_S}, \quad (7)$$

where α_{sk} is the skew angle and Ns is the number of slots. The skew angle is given in Equation (7).

Average values of load torques are nearly same values for even one slot pitch skewed motor result in terms of average load torque are coherent with the non-skewed motor model. The relative torque ripples can be calculated as follows:

$$T_{ripple} = \frac{(T_{max} - T_{min})}{T_{avg}} \quad (8)$$

By applying the equation (8), the torque ripple results and skew angles have been evaluated in Table 3 at the speed of 800rpm.

Table 3. Torque ripple results

α_{sk}	0	2.5	5	7.5	10
Torque ripple %	59.1	53.1	38.6	29.32	24.3
Average Torque N.m	218	210	203	197	188

It should be noted that if increasing skew angle, the torque ripple is reducing but the average torque will be down also. Thus, with the starting mode and muximum speed, it can get the higher torque ripple and the bigger average torque.

6. CONCLUSION

The paper has presented a comprehensive design of a PMBLDC motor for electric vehicles. The design is calculated by analytical method, optimized by SPEED software and evaluated electromagnetic characteristics by the FEM. Particularly, thermal calculation is carried out to compare temperature capacities in worst cases. The skewing method is applied to the PM surface mounted type BLDC motor for eliminating torque ripples. To observe the skewing effect, the stator lamination layers are skewed with different angles. The best skewing angle is determined by number of stator slots and cogging period with a parametrical study.

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