Permanent magnet BLDC Motor designs with skewing for torque ripple and cogging torque reduction

Thiết kế động cơ một chiều không chổi than nam châm vĩnh cửu gắn chéo rãnh stator nhằm giảm mô men đập mạch

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Keywords

Permanent Magnetic Brushless Direct Current (PMBLDC), Finite Element Method (FEM).

Abstract

Permanent magnet BLDC motor can bedesigned with different rotor configurations based on thearrangement of the permanent magnets. Rotorconfigurations strongly influence the performance ofpermanent magnet electrical machines. The aim of thispaper is to compare and evaluate different rotorconfigurations for PMBLDC motor with or without skewed stator slot. Most of theapplications prefer surface mounted permanent magnetdesign due to its ease of construction and maintenance in [1,2]. FE methods have been used for analysis andcomparison of differentgeometry parameters and configurations in [3,4,5].

This paper describes a comprihensive design of a three phase PMBLDC motor 35 kW for electrical drive application.An optimal design of PMBLDC motor have been implemented by analytical and simulation methods.

In this paper, skewing slot is applied to the PM surface mounted Brushless DC 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. With determined skewing angle, the cogging torque eliminated theoretically and flux density space harmonics are also reduced.

1. Introduction

Permanent magnet (PM) brushless DCmotors have been widely used because of theirattractive features like compactness, low weight, highefficiency, and ease in control [1,2]. The reliability ofBLDC motor is high since it does not have any brushesto wear out and replace. The stator consists of stackedsteel laminations with windings placed in the slotswhere as the rotor is made of permanent magnet thatcan vary from two to twelve pole pairs with alternatenorth and south poles.

Different rotor configurations are available forPMBLDC motor namely surface mounted PM designwith interior or exterior rotor, interior PM design withburied magnets etc., each having specific strengths andweaknesses [4]. Among these the radial-flux, surfacemounted type is commonly used for its simplicity formanufacturing and assembling. But this type of motorsprovides low inductance value so that the overall timeconstant is reduced. This introduces high torque ripplewhich is undesirable in servo applications. Thereforeanother rotor design with permanent magnet embeddedinside the rotor namely tangentially magnetized PMmotors are considered. Performance evaluation of thesetwo motors is discussed in this paper. FEM has been applied to design BLDC motor widely in [3,4,5].

Finite Element (FE) analysis using FEMM software is done for both the motorconfiguration in order to make a comparison. Thesimulation results are presented this paper.

2. PMBLDC Motor Analysis

The analysis is being carried out for a threephase BLDC motor.Magnet Vacodym 677HR is magnet material used due to its good thermal stability allowing its use inapplications exposed to high temperature about 180 C. The flux density is selected about 0.8 T.

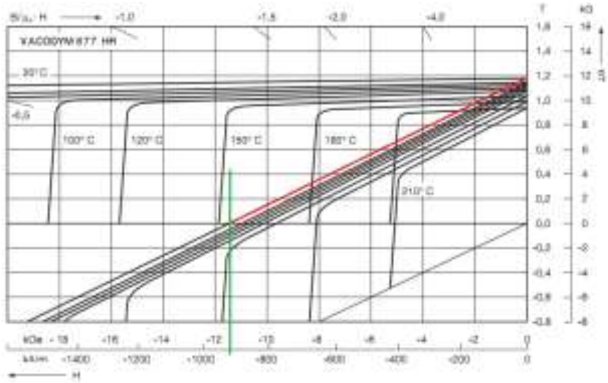


Fig 1. *Magnetic properties of 677HR*

Permanent factor is calculated based on following equation:

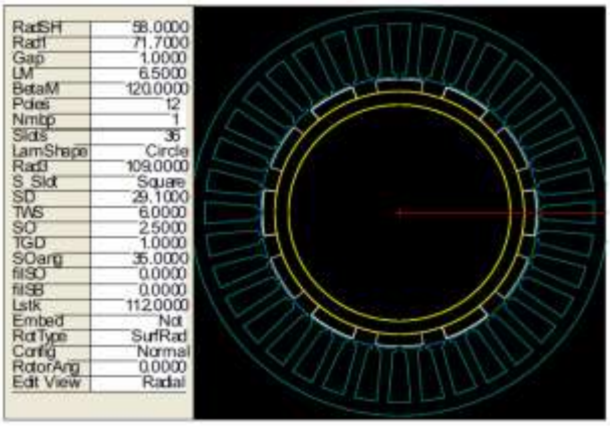
$$\mu_0\mu_m = \frac{\Delta H}{\Delta B} \rightarrow \mu_m = \frac{\Delta H}{\mu_0 \Delta B} = \frac{1.18T}{915kA/m \cdot \mu_0} = 1.026 \qquad (1)$$

Thegeometry specifications of the motor used for the analysis arelisted in table I.

Table I. 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

The design requirements are low cost, overload capacity, complex controller, efficiencyand reliability. For electric vehicle applications, the manufacturing cost, complex controller are not so important, but efficiency is the first priority of this design. With those requirements above, a layout of BLDC motor was calculated by SPEED software shown in fig 2.



RadSH	58.0000
Rad1	71.7000
Gap	1.0000
LM	6.5000
BetaM	120.0000
Poles	12
Nmbp	1
Slots	36
LamShape	Circle
Rad3	109.0000
S_Slot	Square
SD	29.1000
TWS	6.0000
SO	2.5000
TGD	1.0000
SOang	35.0000
filSO	0.0000
filSB	0.0000
Lstk	112.0000
Embed	Not
RotType	SurfRad
Config	Normal
RotorAng	0.0000
Edit View	Radial

Fig 2.*Layout of a BLDC Motor p=12, Z=36*

Based on this design,some basic performances are shown in fig 3. 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 149.7 Nm with 200V and 180A.

Fig 3.*Performances of a BLDC Motor*

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 660 rpm with a current I=959,4 A and the efficiency is quite low about 66%. Other basic parameters are expressed in fig 4.

Fig 4.*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 FEM

Applying ranging method, some basic parameters are adjust to get 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 11 mm and the controlling angle Th0 is from 20 to 40 degree. An optimal design is shown in fig 5 with a maximum efficiency of 96,11%. The slot factor is less than 0.5.

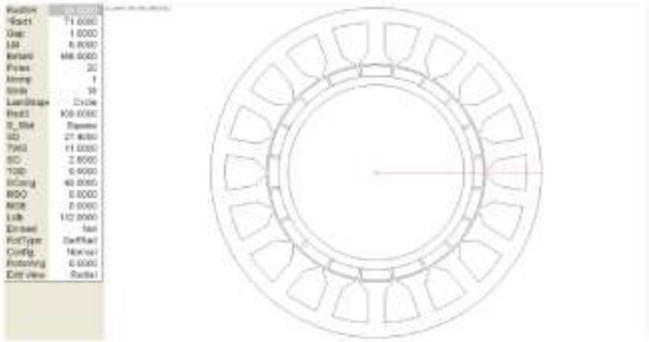


Fig 5.*An optimal design of PMBLDC Motor p=20, Z=18*

Some operation points have been recorded to monitor torque performances in Table II. It is easy to know the maximum efficiency of 96,11% at speed of 1600 rpm, the shaft torque is 750 at speed of 200 rpm with a lower efficiency of 39%.

Table II Important operation points

n (rpm)	T (Nm)	η (%)	I (A)	Th0 (^{0})	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 FEMM software. After meshing the geometry model included magnetic, silicon steel and insolation materials, the electromagnetic characteristics have been obtained in fig 6. The flux density distribution of rotor and stator is resulted at 800 rpm and 270A.

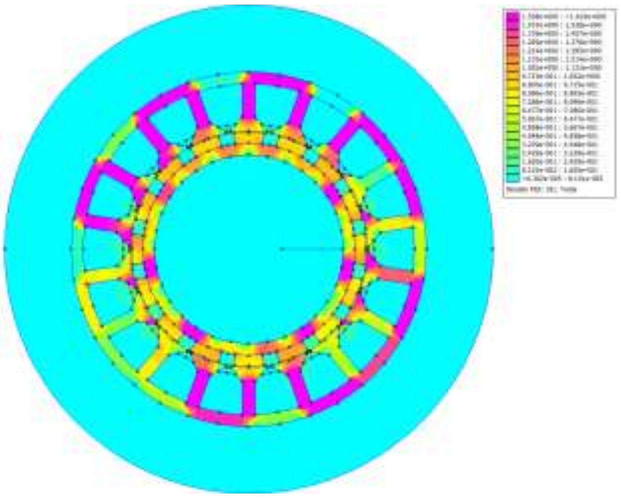


Fig 6.*Flux density results*

Based on this simulation, the electromagnetic torque curves have also determined at different rotor positions from 0 to 360 and I=400A as fig 7.

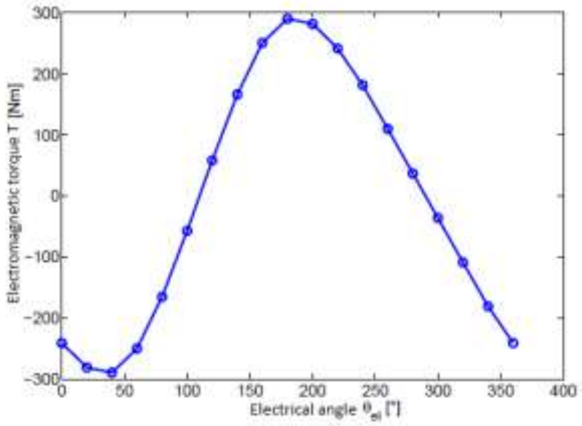


Fig 7. *Electromagnetic Torque curves with current I=400A*

Flux density of air gap has been investigated at different modes such as no-load, full load and 90, 180 degree shift as fig 8. Many steps of rotor position and currents, the torque and flux density results have recorded and saved Matlab files to plot those characteristics.

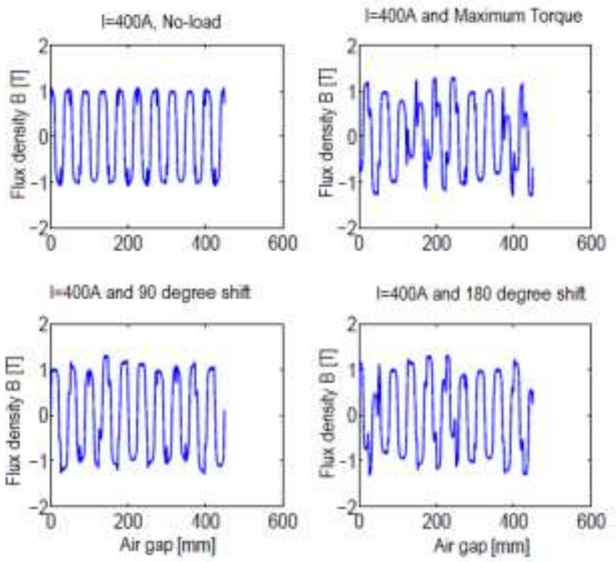


Fig 8. Flux density vs air gap length curves with current I=400A.

Electromagnetic forces were calculated at different speeds in fig 9.

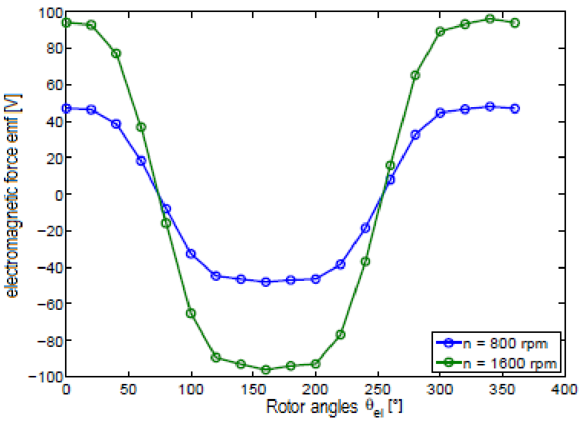


Fig 9. *emf vs speeds.*

The emf can be obtained by analytical method as equations:

$$e=-\frac{d\psi}{dt}=-\frac{d\psi}{d\theta}\cdot\frac{d\theta}{dt}$$

$$=-\frac{d\psi}{d\theta}\square 2\pi\square n\approx-\frac{\Delta\psi}{\Delta\theta}\square 2\pi\square n \qquad (2)$$

Flux linkage and inductance were implemented by FEM simulation as results.

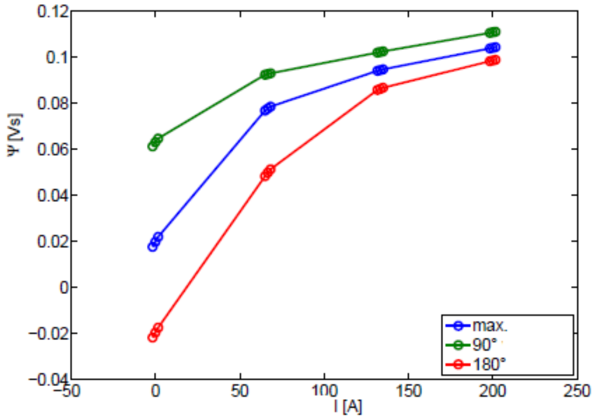


Fig 10.*Flux linkage vs current*

The inductance can inferred from flux linkage curves as equation:

$$dL = \frac{d\psi}{di} \approx \frac{\Delta\psi}{\Delta i} \tag{3}$$

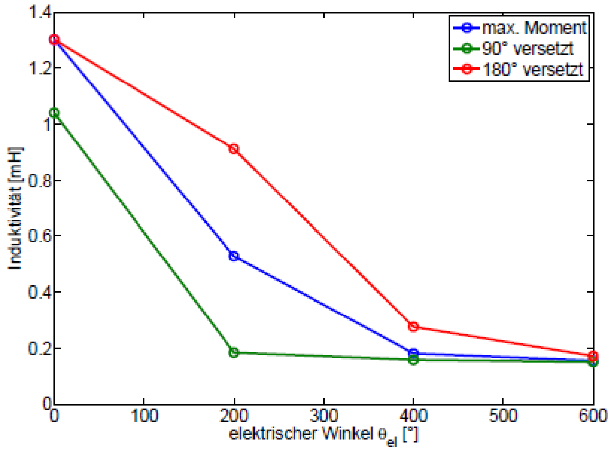


Fig 12. *Inductance curves vs rotor angles*

The simulated results are useful for dynamic investigation and basic parameters for torque and speed controllers.

4. Skew angle calculation

Skewing method is used frequently in BLDC motors for eliminating this cogging torque. With optimum skew angle, cogging torque can be eliminated theoretically. Skewed slots for the stator lamination layers are illustrated in Fig13. Any consecutive slots are numbered as 1 and 2 in Fig 13(a) to show the beginning position for the first layer. Depending on optimum skew angle, each layer should be skewed one by one.

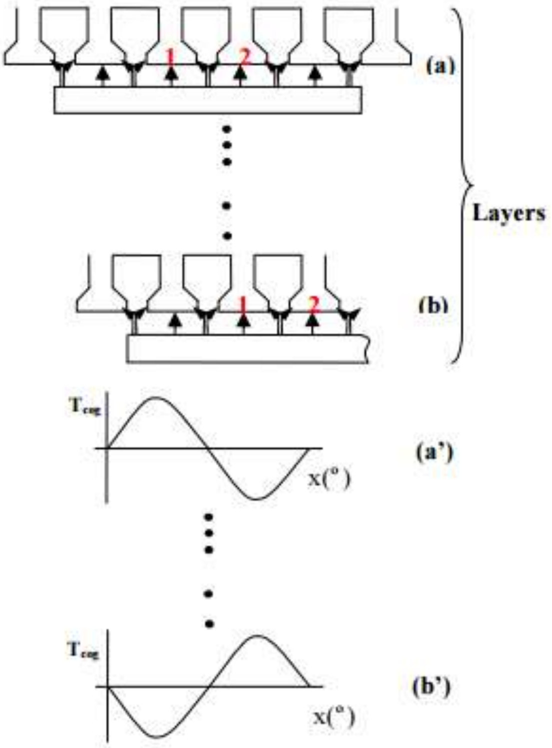


Fig 13.*Cogging torque analysis*

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

$$T_c = \frac{-dW}{d\theta} \tag{4}$$

Tc is the cogging torque, ∂θ is the displacement with mechanical degree, ∂W is the stored co-energy in the air gap.

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

$$T_{skew}(\theta) = \sum_{i=1}^{\infty} K_{sk} \cdot T_i \cdot \sin(iC_p\theta_m + \theta_i) \tag{5}$$

Ksk is the skew factor which is 1 for non-skewed motor laminations. Cp is least common multiple between thenumber of pole and number of stator slots, Ti is absolute values of the harmonics, m θ is the mechanical angle between stator and rotor axis while motor is rotating and represent to the phase angle Ksk, that is skew factor, the defined by

$$K_{sk} = \frac{\sin(iC\pi\alpha_{sk}/N_s)}{iC\pi\alpha_{sk}/N_s} \tag{6}$$

α_{sk} is the skew angle and N_s is the number of slots. Skew angle is given in Equation (5).

Table III Torque ripple results

αsk	0	2.5	5	7.5	10
Torque ripple %	59.1	53.1	38.6	29.32	24.3

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. To relative torque ripples can be calculated as follows:

$$T_{ripple} = \frac{(T_{\max} - T_{\min})}{T_{avg}} \qquad (7)$$

5. Conclusion

The paper has presented a comprehensive design of a PMBLDC motor for electric vehicles. The design was calculated by analytical method, optimized by SPEED software and evaluated electromagnetic characteristics by FEM. Particularly, thermal calculation was carried out to compare temperature capacities in worst cases.

The skewing method is applied to the PM surface mounted type Brushless DC 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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