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Cogging Torque Analysis of the PMSM for High Performance Electrical Motor Considering Magnetic Anisotropy of Electrical Steel

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Abstract

This paper deals with torque and cogging torque analysis of interior permanent magnet (IPM) motor considering anisotropy of electrical steel sheets. Generally, cogging torque is caused by tooth and slot structure in permanent magnet motor. But, magnetizing direction of iron core is changed by each rolling position in the manufacturing process of iron core. In this paper, analysis of cogging torque presents effects of not tooth and slot structures but rolling direction of iron core. It is useful to apply precise electrical motor as EPS.

Keywords: anisotropy, permanent magnet motors, cogging torque, torque ripple

1 Introduction

Permanent magnet synchronous motor(PMSM) is wildly used from home appliance to electric vehicles since PMSM have high power density and efficiency than reluctance and induction motor. Especially application for EPS requires high torque density and precise torque controls. In order to reduce error of torque, many studies are performed for cogging torque in EPS and other applications[1][2].

But in some cases, cogging toques analysis is different from measurement, and this difference appears periodically in rotary motor[3]. In order to find this reason, we take account of anisotropy of iron core permeability. Generally, the rolled steel sheet is made by rolling machine consist of upper roller and below roller. Permeability of iron core can be changed output direction of rolling machine as Fig. 1.

In this paper, cogging torque and torque ripple are studied considering anisotropy of electrical steel sheets. In order to analysis this phenomena, several step is performed. First, B-H data are obtained by measurement at each angle from rolling direction. And the software consists to solve the anisotropy material by FEM. The finite element analysis is used to consider anisotropic material and non-linear algorism. In the result, cogging torque and torque ripple from analysis and measurement are shown according to rotation angle.

This paper is useful the understanding unknown error of the cogging torque, frictions, hysteresis of electric motor in the manufacturing process.

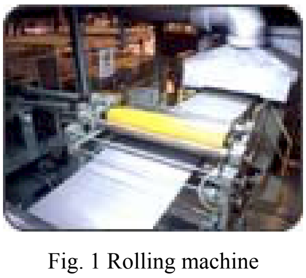

Fig. 1 Rolling machine

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2 Measurement of B-H Curve and Core loss

2.1 Measurement sheet model

B-H data are measured by Single Sheet Test (SST) reference to the angle from rolling direction is shown in Fig.2. The presents specimen for SST, and 7 specimens are cut and the size is 150×150 mm.

The angle is defined from rolling direction in the figure. Reference angle is defined to zero into output direction.

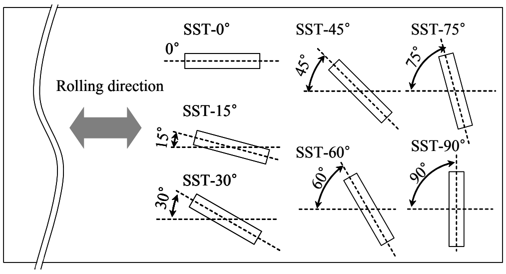

Fig. 2 Cutting of specimens for SST

The test results of SST are shown in Fig. 3. In Fig. 3 it is shown that the lowest B-H characteristics occurs about 45º. Therefore, it is expected that the average B-H data of rolling and cross rolling direction, which is provided by manufacturer will results in difference between analysis and experiments.

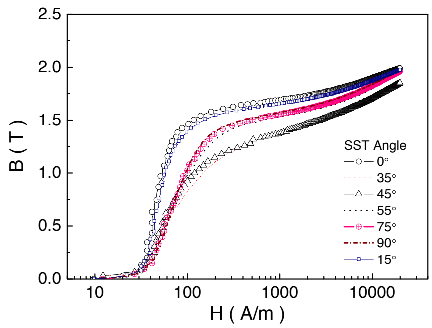

Fig. 3 Measured B-H data according to angle from rolling direction

2.2 Interpolation for FEA

Measured B-H data are interpolated and prepared for 2-dimensional FEA. B-H data consist of B, H, and θ (angle from rolling direction). The straight line method is used for interpolation. After define the direction of flux density of core, selected 2 SST B-H curve. Then non-linear algorism of iron core is used for solve the problems.

B-H data provided by steel manufacturer are limited due to practical reason. In the IPM type motor, flux density in bridge region is generally beyond provided material data. Therefore, flux density should be modeled according to field intensity. For the isotropy analysis, flux density is calculated with relative permeability of air for the increase of field intensity. For the anisotropic analysis, last slope of measured data is maintained.

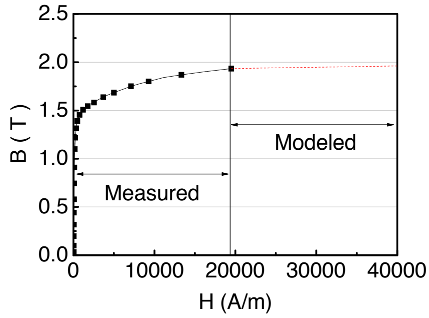

Fig. 6. B-H data modeling

3 Analysis model and theory

3.1 Analysis model

The analysis model has 4-poles and 6-slots with concentrated windings and shown in Fig. 4. The stator outer radius is 117mm and air gap length is 0.7mm. Table I. shows the major motor dimensions and parameters. The fabricated rotor core and completed view is shown in Fig. 5. The model has 2mm of bridge width for the study of the effect of bridge width, and thick bridge can be seen Fig. 5(a).

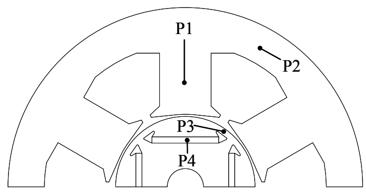

Fig. 4 Rotor and stator structure (1/2 model)

TABLE I
MAJOR DIMENSIONS AND PARAMETERS

Number of poles	4
Stator outer radius (mm)	117
Stator inner radius(mm)	47.4
Airgap length(mm)	0.7
Rotor outer radius(mm)	46
Stack Length(mm)	45
Magnet remanent flux density(T)	1.2
Magnet recoil permeability	1.05
Stator and rotor core material	50PN595

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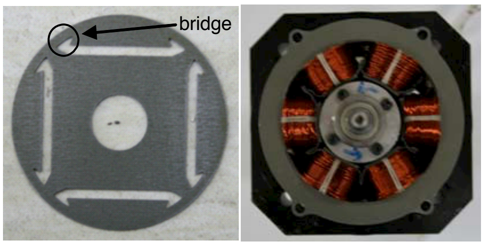


(a) Rotor core (b) Assembled motor.

Fig. 5. Top view of fabricated rotor core and assembled motor

3.2 FEA considering B-H curve

The static field FEM is used for the analysis of the magnetic field. The governing equation for 2-D FE analysis is given by (1).

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=-J_0-J_m \qquad (1)$$

where, A is the z-component of magnetic vector potential, μ is the permeability, J_0 is electrical input current density and J_m is magnetizing current density. The permeability is expressed the measurement data of the magnetic intensity and direction. As shown in Fig. 6, governing equation is solved with the initial permeability of material then flux density and θ are calculated in each element. With the flux density and θ, new permeability is found from B-H data then governing equation is calculated again until the error is converged.

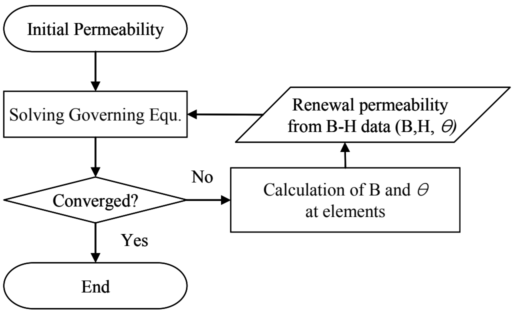


Fig. 6 FEA process take account for the direction of iron core

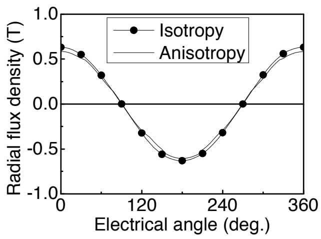
4 Results and verifications

4.1 Flux densities at no load

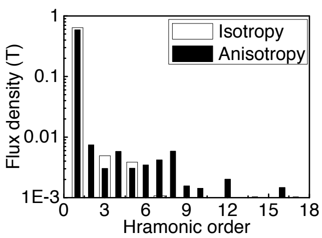
Fig. 7 shows the mesh generation of the model.
Fig. 8 shows the equi-potential line at 0°, 24°.
Fig. 9 shows the flux density variation at no load according to rotor positions of P1 shown in Fig. 4. In the comparison, only main flux density components in each part are presented. For the tooth (P1) and yoke part (P2), Isotropy analysis results show higher flux density in fundamental component. In the bridge part (P3), higher tangential flux density is observed with anisotropy analysis and also higher core loss is expected due to magnitude and harmonics. The Flux density of a P3 part appears high when it is anisotropy, and a harmonic magnitude is higher than isotropy result because of the magnetic permeability changes periodically in anisotropy material. So, a magnetic reluctance is different from a stator part, and because a whole magnetic reluctance is changed, a leakage effect appears greatly from a bridge part.

Fig. 7 Triangle mesh generation (Ele. num. = 15182)

Fig. 8 Equi-potential line at at 0°, 24°.



(a) Flux density



(b) Harmonic analysis

Fig. 9 Flux density of P1(in stator tooth)

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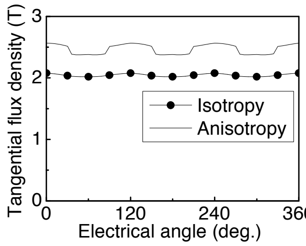
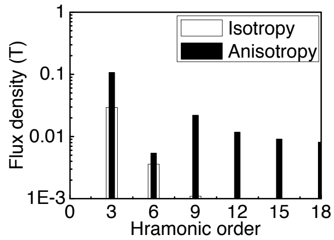


(a) Flux density in bridge (P3)



(b) Harmonic analysis

Fig. 10 Flux density of P3(rotor bridge)

4.2 No load back EMF

No load back EMF is the major motor parameters and should be expected precisely. However, differences between FEA and experiments occur sometimes and this leads to change of the entire motor characteristics. No load line to line back EMF comparisons are shown in Fig. 11.

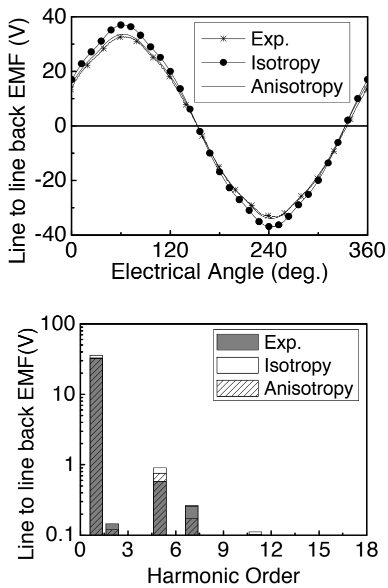


Fig. 11 Comparison of back EMF at 25°C, 1000rpm.

There is significant difference between experiment and isotropy analysis; 11% higher back EMF than experiment. This difference affects to the entire motor performance, such as efficiency, rated current, voltage, etc. By considering anisotropy of core material, back EMF is precisely calculated; 1.9% higher than experiment.

4.3 Cogging Torque

Fig. 12 shows cogging torque analysis result and experiment result according to analysis method. In case of isotropy, a period of cogging torque is 30° because of mechanical combination of 4 poles and 6 slots. In the case of anisotropy analysis, peak value for 40 ~ 50° is low and the repeatedly occur. In the test result, cogging torque decreases according to angle, and periodicity appears. In this result, experiment result is similar with analysis result at several points, but magnitude of cogging torque is different from test result. The reason of difference is predicted magnet performance and the measurement machine condition is different. But the decreasing waveform of cogging torque is similar with test result.

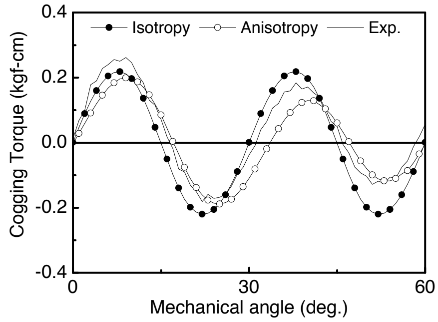


Fig. 12 Comparison of cogging torque

5 Conclusion

Cogging torque is very important factor in high performance and precise electrical motor. In this paper, magnetic anisotropy is considered for cogging torque analysis. At manufacturing process of iron core, according to rolling direction, magnetic characteristic is changed. Therefore, cogging torque analysis is take account of core rolling direction. And this paper will be help to get more precise result compared with real phenomena in electrical motor.

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