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## WELCOME TO INTERMAG EUROPE 2008 CD

The INTERMAG Europe 2008 Conference is to be held in the *Palacio Municipal de Congresos de Madrid*, from **May 4 to May 8, 2008**.

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- CL-10. A STUDY ON THE IRREVERSIBLE MAGNET DEMAGNETIZATION IN SINGLE-PHASE LINE-START PERMANENT MAGNET RELUCTANCE MOTOR.** J. Hong<sup>2</sup>, H. Nam<sup>3</sup> and T. Kim<sup>1</sup>*1. Electrical Engineering, Gyeongsang National University, Jinju, South Korea; 2. Hanyang University, Seoul, South Korea; 3. LG Electronics, Changwon, South Korea*
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- CL-12. Characteristic analysis of Permanent Magnet Motor Considering Anisotropic Characteristics of Electrical Steel Sheets.** S. Kwon<sup>1</sup>, J. Lee<sup>1</sup>, K. Ha<sup>2</sup> and J. Hong<sup>1</sup>*1. Department of Mechanical Engineering, Hanyang Univeristy, Seoul, South Korea; 2. POSCO Technical Research Laboratories, Pohang, South Korea*

# Characteristic analysis of Interior Permanent Magnet Synchronous Motors Considering Anisotropic Characteristics of Electrical Steel

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This paper deals with characteristics of interior permanent magnet synchronous motor considering anisotropic characteristics of electrical steel sheets. Motor characteristics of back electro-motive force (EMF), d-q axis inductances, and core loss are calculated by FEA considering anisotropy of electrical steel sheets and compared to the results from experiment and general FEA; using single material data of isotropic electrical steel sheets for the entire core region. An interior permanent magnet motor is fabricated and analysis results are verified by experiments. In the verification, 11% higher back EMF than experiment is calculated by general FEA while 2% higher back EMF by considering anisotropy of material. For the fabrication, rotational stacking is not applied.

**Index Terms**— Finite element analysis, Permanent magnet motors, Magnetic materials

## I. INTRODUCTION

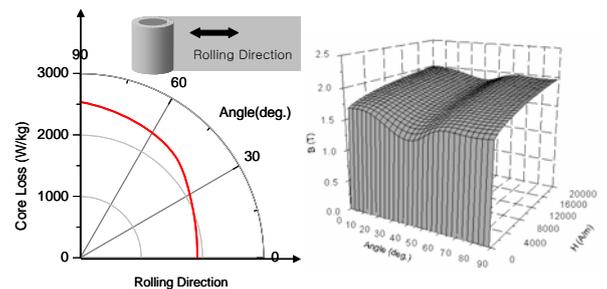
Finite Element Analysis (FEA) is generally used for the analysis and design of electrical machines. To improve its accuracy, more precise material data should be provided. Electrical steel sheets are classified into isotropic and anisotropic, and isotropic steel sheets are generally used for electrical motors and anisotropic steel sheets are used for transformer. Actually, isotropic steel have anisotropic B-H and core loss characteristics reference to rolling direction and the average value of rolling and transversal direction is provided by manufacturer. Therefore, using average characteristics of electrical steel sheets leads to difference between experimental and FEA results. Measurement and analysis method considering anisotropic material characteristics are researched [1], however, it requires complex technique in measurements and large computation time solving governing equation for FEA. Therefore this paper presents simple but clear test method for anisotropic electric steel core and analysis method considering anisotropic materials. Simple test for measuring core loss and B-H data for anisotropic materials and FEA analysis using measured data are presented.

For the verification of analysis, an interior permanent magnet motor is fabricated and tested. Permanent magnet motors have higher power density than other type motor of induction motor, switched reluctance motors, etc. Especially interior permanent magnet (IPM) type motors utilize both magnetic and reluctance torque, they have higher power density than surface permanent magnet motor and this leads to growing interests for wide applications. Therefore many IPM type motors are designed and sometimes significant difference of motor parameter occurs between experiment and FEA result [2].

## II. MEASUREMENT OF B-H AND CORE LOSS DATA

B-H and core losses are measured by Single Sheet Test (SST) reference to the angle from rolling direction and results

are shown in Fig. 1, and angle is defined from rolling direction in the figures. In Fig. 1 it is shown that the lowest B-H characteristics occurs about 45°. Therefore, it is expected that the average B-H data of rolling and cross rolling direction will results in difference between analysis and experiments. Fig. 2 presents specimen for SST, as shown in Fig. 2, 7 specimens are cut and the size is 150×150 mm.



(a) Core loss data

(b) B-H data

Fig. 1. Measured core loss data (0.6T, 50Hz) and B-H data according to angle from rolling direction by SST.

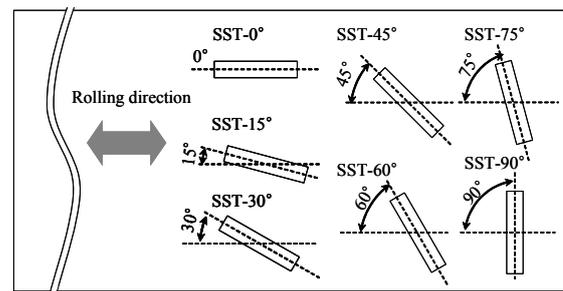


Fig. 2. Cutting of specimens for SST.

## III. ANALYSIS METHOD AND PROCEDURE

### A. Analysis process

Measured B-H and core loss data are interpolated and prepared for 2-dimensional FEA. B-H data are consist of B, H, and  $\theta$  (angle from rolling direction), and core loss data are consist of B, core loss (W/kg), and  $\theta$ . Using B-H data, FEA is

conducted then core loss is calculated [2] with measured core loss data. Solving procedure of FEA is shown in Fig. 3. As shown in Fig. 3, governing equation is solved with the initial permeability of material then flux density and  $\theta$  are calculated in each element. With the flux density and  $\theta$ , new permeability is found from B-H data then governing equation is calculated again.

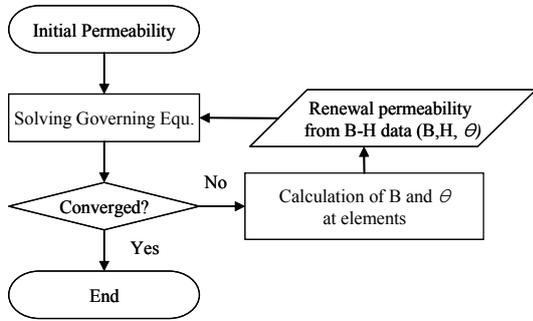


Fig. 3. FEA process.

#### IV. FEA RESULTS AND VERIFICATIONS

##### A. Analysis Model

Table I. shows the major motor dimensions and parameters. The analysis model has 4-poles and 6-slots with concentrated windings and shown in Fig. 4, and 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).

##### B. Flux densities at no load

Fig. 6 shows the flux density variation at no load according to rotor positions from P1 to P4 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.

In the permanent magnet part (P4), higher eddy current loss in permanent magnet is expected when anisotropy is considered due to higher harmonics and fundamental component flux density. Even though higher operating point of permanent magnet, higher leakage flux through bridge part leads to decreased linkage flux.

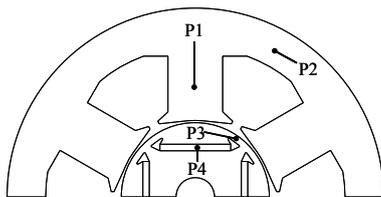
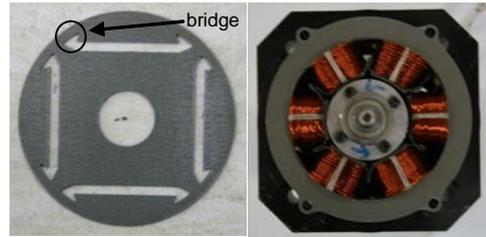


Fig. 4. Rotor and stator structure (1/2 model), and P1~P4 represents the position of elements to estimate flux densities and core loss densities.

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 relative recoil permeability	1.05
Stator and rotor core material	50PN595



(a) Rotor core.

(b) Assembled motor.

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

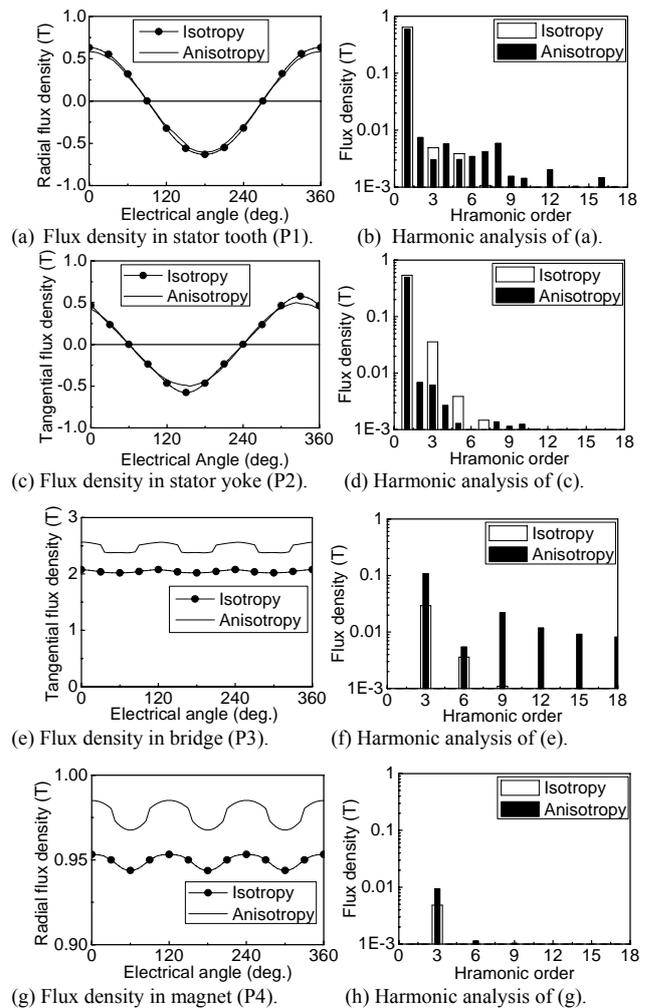


Fig.6. Flux density and harmonic analysis at P1~P4 in Fig. 4.

C. 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. 7. 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.

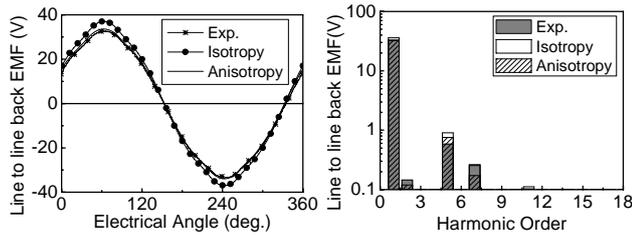


Fig. 7. Comparison of line to line no load back EMF at 25°C and 1000rpm.

D. Core loss and cogging torque

Core losses are calculated by FEA based on measured core loss data [3]. No load core losses versus speed are shown in Fig.8, and there is small difference between two analysis results of the studied model. For the separation of core loss from mechanical loss in the experiment, a rotor with non-magnetized permanent magnet is additionally fabricated for mechanical loss measurement.

Fig. 9 shows the cogging torque comparison, the peak value can be acceptable for both analysis results. Measured cogging torque wave form is asymmetric positive and negative value, and this is shown well with anisotropy analysis.

Fig. 10 shows the core loss density distributions and Table II. shows core loss densities for P1~P3. There is no significant in the stator part, however, in bridge part higher core loss density is observed when anisotropy is considered. Higher core loss density leads to higher local heating in bridge area, and this result in weakening of mechanical strength of bridge area. For the magnetic design aspect of IPM motor, bridge area are preferred to be as thinner as possible to reduce leakage flux of permanent magnet.

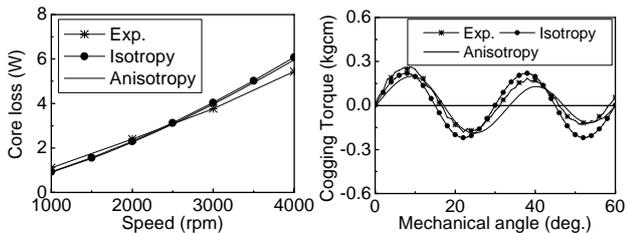
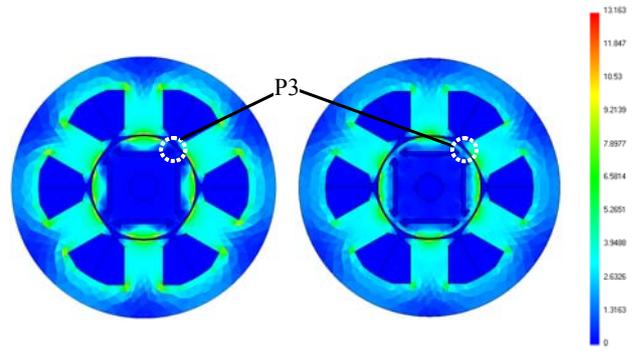


Fig. 8. Comparison of core loss Fig. 9. Comparison of cogging torque



(a) Isotropy analysis (b) Anisotropy analysis

Fig. 10. Core loss density distribution.

TABLE II  
CORE LOSS DENSITY COMPARISON AT P1~P3 AT 25°C, 4000RPM (W/KG)

Position	Isotropy	Anisotropy
Tooth (P1)	3.006	3.067
Yoke (P2)	2.263	2.070
Bridge (P3)	0.261	2.435

E. Inductance

Inductance is the major motor parameter with back EMF. Especially for the IPM type synchronous motor, d-axis inductance determines the characteristic current with no load flux linkage, therefore, determines the entire motor characteristics. There are a number of methods available to determine the inductances by FEA [4],[5]. Three phase flux linkage FE method is used for inductance calculation and its results are shown in Fig. 11 18% and 7% higher d-q axis inductances are estimated by anisotropy analysis.

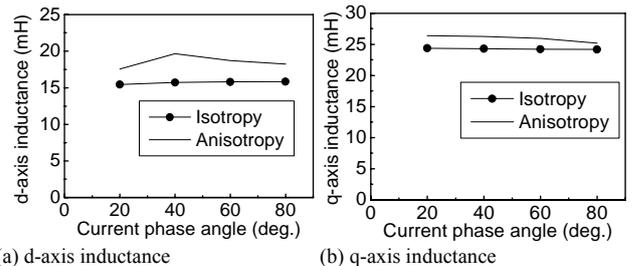


Fig. 11. Comparison of d-q axis inductance (1Arms)

F. Output Performance

To compare output performances due to parameter differences, d-q axis equivalent circuit simulation is used and parameters are shown in Table III and d-q axis equivalent circuit of IPMSM are shown in Fig. 11. In Table III, linkage flux by permanent magnet ( $\psi_a$ ), d- and q-axis inductances are calculated by FEA and core loss resistance is modeled considering rotating speed using core loss in Fig. 8 and  $\psi_a$  in Fig. 7 [7].

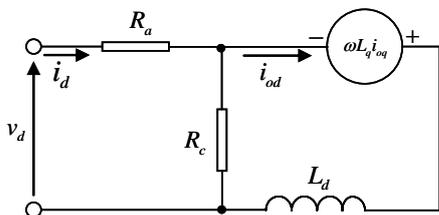
Output power and torque vs. speed of the motor are shown

in Fig. 12. In order to get performance shown in Fig. 13, maximum torque per and maximum efficiency control is applied to constant torque region and constant power region respectively. The simulation results are not necessarily precise at this point, and relative difference of performance is focused.

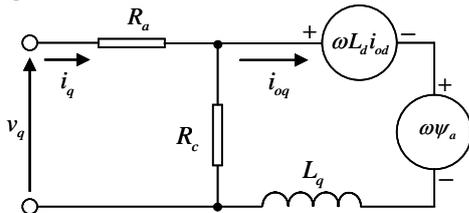
In the comparison of line to line voltage, anisotropy simulation shows lower voltage increases due to lower back EMF. For the input current, due to lower linkage flux by permanent magnet, anisotropy simulation shows higher input current for required output torque in most operating region. Maximum current for anisotropy and isotropy simulation are 1.52 and 1.4Arms respectively. Maximum efficiency is found at 4000rpm in both analysis and 93% for anisotropy and 93.4% for isotropy analysis. In the low speed region, minimum efficiency of 79.5% for anisotropy and 81.8% for isotropy analysis are occurred.

TABLE III.  
PARAMETERS FOR D-Q AXIS EQUIVALENT CIRCUIT ANALYSIS AT 75°C

	Isotropy	Anisotropy
Line to line voltage (Vrms)	100	100
Pole pair	2	2
$\Psi_a$ (Wb)	0.09368	0.0857
<i>d</i> -axis inductance (mH)	Fig. 10(a)	Fig. 10(a)
<i>q</i> -axis inductance (mH)	Fig. 10(b)	Fig. 10(b)
Phase resistance ( $\Omega$ )	1.28	1.28
Core loss resistance ( $\Omega$ )	$3.23+24.93\omega_e^{0.63}$	$2.50+21.7\omega_e^{0.63}$



(a) d-axis equivalent circuit.



(b) q-axis equivalent circuit.

Fig. 12. d-q axis equivalent circuit considering iron loss

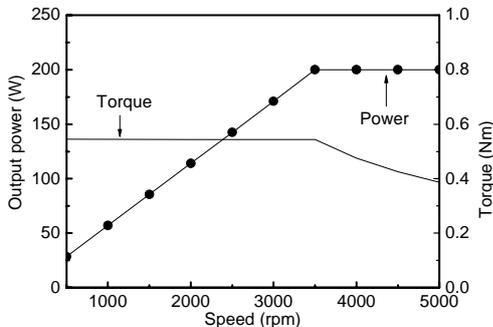


Fig. 13. Output torque and power-vs.-speed.

## V. CONCLUSION

This paper has presented measurement of anisotropic core material and FEA considering anisotropy. Parameters of IPMSM are calculated and verified by experiments. It is found that the back EMF, inductance, and distribution of core loss density can be significantly different by considering anisotropy of material and this leads to the difference of output performances.

Presented approaches to estimate motor parameters can be a good reference for solving problems of differences between FEA and experiments. The differences between FEA and experiments in IPM type motor does not always take places due to anisotropy of material, and rotating lamination alleviate the effect of anisotropy. Therefore, lamination effect and magnetic design to avoid the differences will be next study.

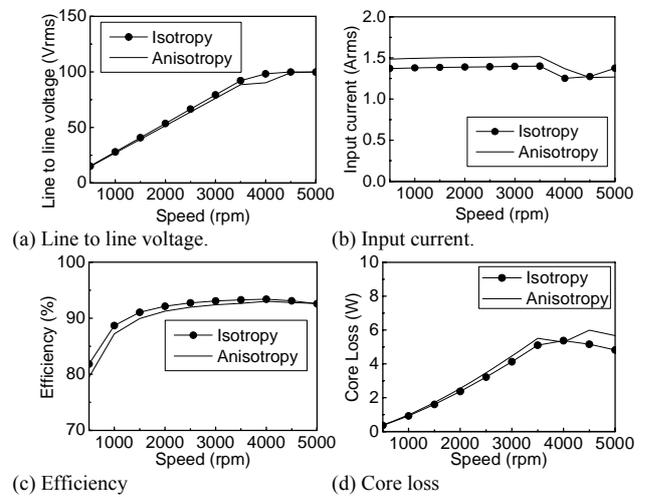


Fig. 14. d-q axis equivalent circuit simulation results at 75°C.

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