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# Anisotropy of Resistivity of Nd-Fe-B Magnets - Consequences in Eddy-Current Calculations

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***Abstract*—In the latest research, the electrical resistivity of Nd-Fe-B-material is found to be anisotropic. The value for electrical resistivity in the orientation direction is higher than the resistivity in direction perpendicular to the orientation direction. This anisotropy must be taken into account in accurate eddy-current calculations. This is shown, by modeling the eddy-current losses of a permanent magnet motor with 3D and 2D FEM using both anisotropic and isotropic resistivity and comparing the results.**

***Keywords*—Rare Earth, Permanent Magnet, Conductivity, Resistivity, Synchronous Motor, Finite-Element Method.**

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## I. Introduction

THE electrical resistivity of sintered Nd-Fe-B permanent magnet material is assumed to be constant and isotropic in IEC standard [1] and in the datasheets of the magnet manufacturer [2]. The latest research has revealed an anisotropy of electrical resistivity [3]. This anisotropy has significant consequences in eddy-current calculations of permanent magnet machines.

The value of electrical resistivity in IEC standard [1] at room temperature is 1.4…1.6 μΩm. The temperature dependence of this value is not reported in the standard. According to the measurements in [3], the value of electrical resistivity in the orientation direction of the magnet material (axial resistivity) corresponds to the values in the standard. However, the electrical resistivity to the direction perpendicular to the orientation direction (transversal resistivity) is about 18 % smaller. The temperature dependence of these resistivities is also reported in [3] for the temperature range -40˚C…+150˚C. The temperature dependence of resistivity in transversal direction is about linear over this temperature range, but the temperature dependence in axial (orientation) direction shows clearly non-linear behavior.

In permanent magnets in permanent magnet machines, the eddy-currents can be caused by the harmonics of the frequency converter input or by the stator slotting. The eddy-currents caused by the frequency converter input waveform are circulating around the magnetization axis, which means that the transversal resistivity should be used. Before, only axial value has been available and thus, previous eddy-current calculations have had a systematic calculation error.

## II. The Model

In this paper, a six-pole surface-magnet machine is modeled using commercial FEM software: FLUX by CEDRAT. The modeling is performed in 2D and in 3D. The purpose of the modeling is to study the effect of anisotropy of resistivity in eddy-current calculations. Also, the difference of 2D and 3D results will be considered.

### A. *Machine*

One sixth of a six-pole surface-magnet machine is modeled. Only one half of the magnet length was modeled in 3D. The working temperature is assumed to be 80°C. The main parameters of the machine can be found in Table I. Fig. 1 shows a cut of the machine.

TABLE I
MAIN PARAMETERS OF MODELED MACHINE

| Parameter: | Value |
|---|---|
| Outer diameter of stator | 254 mm |
| Inner diameter of stator | 165 mm |
| Core length | 150 mm |
| Number of poles | 6 |
| Number of stator slots | 36 |
| Connection | Delta |
| Rated speed | 6000 rpm |
| Rated voltage | 400 V |
| Rated power | 45 kW |
| $B_r$ of the magnets in 80˚C | 1.03 T |
| $\mu_r$ of the magnets in 80˚C | 1.05 |
| Magnets per pole (circumferentially) | 5 |

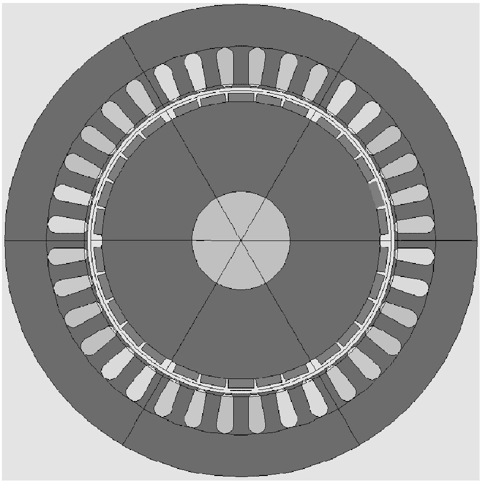

Fig. 1. Structure of the modeled machine.

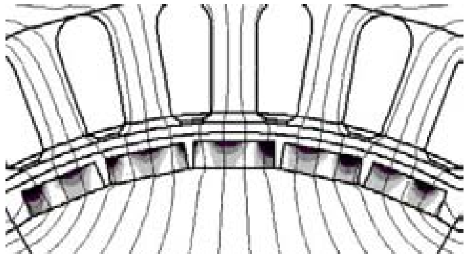

Fig. 2. The eddy-current density in the 2D-modeled permanent magnet motor. The dark spots have the highest current-density.

TABLE II
RESISTIVITY OF ND-FE-B MATERIAL SAMPLES [3]

| Direction | Resistivity at 20°C (μΩ m) | Resistivity at 80°C (μΩ m) |
|---|---|---|
| Axial | 1.54 | 1.62 |
| Transversal | 1.26 | 1.32 |

### *B. Input Current*

The effects of the eddy-currents are calculated with two different sinusoidal current waveforms and also without any current input:

- 300 Hz, 92A,
  which corresponds to the fundamental output frequency of the converter
- 3 kHz, 9.2 A,
  which corresponds to the tenth harmonic of the fundamental output frequency
- 0 A

The last case without any current input was calculated to see the effect of the space harmonics. This input was used in 3D calculations only. In all these cases, the rotor is rotating at constant speed of 6000 rpm.

### *C. 2D Model*

The 2D calculations were performed using FLUX 2D v9.2.2. The mesh had 1449 second-order elements and 3774 nodes. The air-gap was modeled using two layers of elements.

In 2D calculations the current can flow only in one direction: perpendicular to the modeled plane. This means, that the anisotropy of resistivity cannot really be modeled in 2D. Anyway, 2D calculations were performed using both transversal and axial value of resistivity for comparison purposes. The used values of resistivity have been selected according to the measurements presented in [3]. The selected values are presented in Table II both at the room temperature and at the working temperature of the machine (80°C).

A current density plot with 300 Hz and 92 A of the modeled machine is presented in Fig. 2.

### *D. 3D Model*

One pole width of the machine was modeled in 3D using FLUX 3D v10.2.1 by CEDRAT. The mesh had 9110-15305 linear elements and 5797-9120 nodes. The whole length of the machine is 150 mm, but only a half of the length of a single magnet was modeled. There were three magnet sizes:

- 30 mm x 13.5 mm x 4.5 mm
- 10 mm x 13.5 mm x 4.5 mm
- 5 mm x 13.5 x 4.5 mm
  (Axial x circumferential x radial)

The magnets were magnetized diametrically in radial direction.

At the mid-plane of the magnet, boundary conditions with tangential magnetic field (and normal current) were applied. At the other end of the magnet, there was 0.5 mm of air before the end of the geometry. This correspond half of air gaps between the magnets inside the rotor. On the sides of the geometry, the anticyclic boundary conditions were used. Rest of the structure has boundary conditions with tangential magnetic field. The picture of the 3D geometry is presented in Fig. 3.

The 3D calculations were performed using both isotropic and anisotropic resistivity of the magnet material. In isotropic case the resistivity was 1.32 μΩm. In anisotropic case, the resistivity in the axial direction (or in the magnetization direction) was 1.62 μΩm. In the transversal directions (or in the directions perpendicular to the magnetization direction) the resistivity was 1.32 μΩm.

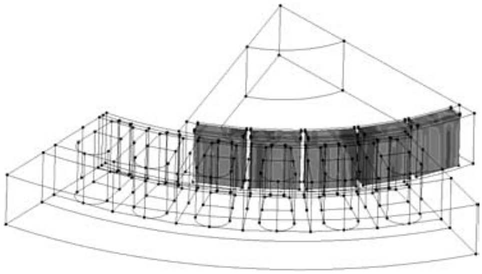

Fig. 3. The geometry and the eddy-current density in the 3D-modeled permanent magnet motor.

## III. Results and Discussion

### A. 2D Results

The results of 2D calculations are presented in Table III. The results of 3D calculations are presented in Table IV.

In 2D calculations the value for transversal resistivity should be used, because the current can flow in 2D calculations only perpendicular to the magnetization direction. The use of axial resistivity would cause a difference of some 16 % in the eddy-current loss results when compared to results acquired with transversal resistivity (Table III). Because the value of transversal resistivity (1.32 μΩm) is a lot less than the value in standard [1] (1.4…1.6 μΩm), the previous calculations using these values have a systematic error.

The 2D modeling does not take the end-effects of the machine into account: for example, there are stray-fields at the end of the machine, which are excluded. However, if the rotor is very long, these stray-fields can be ignored. The same applies to the long conductors like damping bars in the rotor: the end-effects of the eddy-currents in long conductors can be ignored if the rotor is long enough.

The eddy-currents in a magnet, however, cannot be modeled accurately with 2D analysis, as can be seen by comparing the results in Table III and Table IV: The eddy current loss by 2D calculations with transversal resistivity is some 110 % larger for the input frequency of 300 Hz and some 40 % larger for the input frequency of 3 kHz. This is because even in a long machine, the magnet pole is constructed of single pieces in axial direction of the machine. In the modeled machine, for example, the core length of 150 mm was built using five magnets with length of 30 mm. Thus, there are end-effects of eddy-currents in each magnet and not just at the ends of the whole rotor.

### B. 3D Results

In 3D calculations the eddy-currents calculated by using isotropic and anisotropic resistivity do not show very large difference.

It was noticed, that the circulating eddy-current in a magnet is not planar. It can be seen in Fig. 4, that there is also vertical currents in the end of the magnet. This means, that the anisotropy must have an effect on the eddy-current especially in the magnet ends. By comparing the results in Table IV this can be seen: the difference of the eddy-current results with anisotropic and isotropic resistivity is larger for shorter magnets.

By comparing the results in Table IV, it can be seen, that the shortening of the magnet by one third, from 30 mm to 10 mm decreases the eddy-current loss by 28 %. The shortening by one sixth to 5 mm decreases the eddy-current loss by 68 %. This is in accordance with the results in [4]. Fig. 5 shows the eddy-current distribution from the top of the magnet in the case of 10 mm long magnets.

The eddy-current loss in 30 mm long magnets with tenth harmonic (3 kHz, 9.2 A) is more than three times larger than the eddy-current loss with the basic frequency (300 Hz, 92 A). This is because in these calculations the rotor rotates at the rated speed, and thus the fundamental frequency (300 Hz) just increases slot harmonics, but the tenth harmonic (3 kHz) also creates time harmonics. In addition, tenth harmonic induces similar eddy current density distribution along the magnetization direction, while slot harmonics with fundamental frequency induces currents along the rotor length in the air gap sides of the magnets. Therefore, in the ends of the magnets there are larger radial eddy current components with the fundamental frequency, which causes larger effect of anisotropy of the magnets of current machine. The eddy-current density distribution with fundamental frequency can be seen in Fig. 6 and with the tenth harmonic in Fig. 7.

TABLE III
EDDY-CURRENT LOSSES IN 2D CALCULATIONS

| Magnet length (mm) | Supply (Hz) | $P_{EDDY}$ (W) (ρ = 1.62 μΩ m) | $P_{EDDY}$ (W) (ρ = 1.32 μΩ m) | Diffe-rence |
|---|---|---|---|---|
| 30 mm | 300 | 65.8 | 77.9 | -15.5 % |
| 30 mm | 3000 | 142.2 | 168.4 | -15.5 % |

TABLE IV
EDDY-CURRENT LOSSES IN 3D CALCULATIONS

| Magnet length (mm) | Supply (Hz) | $P_{EDDY}$ Anisotropic (W) | $P_{EDDY}$ Isotropic (W) | Diffe-rence |
|---|---|---|---|---|
| 30 mm | 0 | 5.093 | 5.030 | -1.2 % |
| 30 mm | 3000 | 121.30 | 121.31 | +0.1 % |
| 30 mm | 300 | 45.45 | 45.49 | +0.09 % |
| 10 mm | 300 | 26.63 | 26.74 | +0.4 % |
| 5 mm | 300 | 11.90 | 12.06 | +1.4 % |

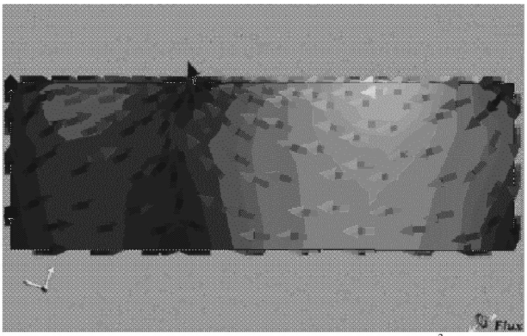

Fig. 4. The vector plot of eddy-currents in 10 x 13.5 x 4.5 $mm^3$ magnet from the magnet end. The vertical current component can be easily seen.

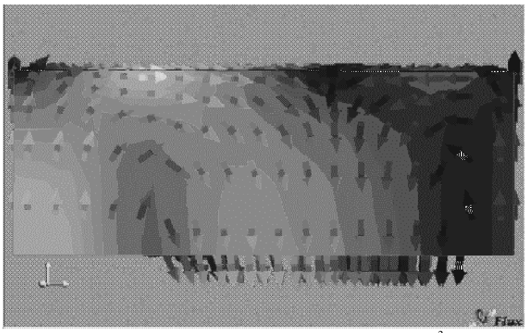

Fig. 5. The vector plot of eddy-currents in 10 x 13.5 x 4.5 $mm^3$ magnet from the topside of the magnet (magnet side perpendicular to the magnetization direction). Only a half of the magnet is modeled.

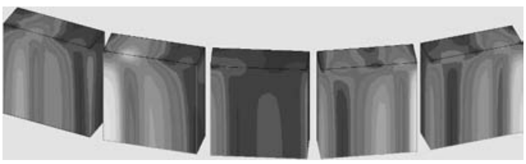

Fig. 6. The eddy current loss density in (the halves of) 30 mm long magnets with sinusoidal input of 300 Hz.

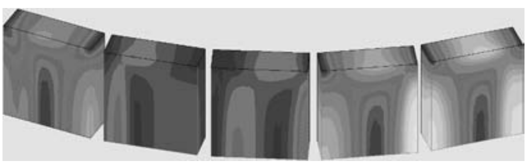

Fig. 7. The eddy current loss density in (the halves of) 30 mm long magnets with sinusoidal input of 3 kHz (tenth harmonic of the converter input frequency).

## IV. CONCLUSION

The eddy-currents of a six-pole surface-magnet machine were modeled in both 2D and 3D using commercial FEM software. The effect of the anisotropic resistivity of Nd-Fe-B magnet material on eddy-currents was studied.

It was shown, that the eddy-currents in a permanent magnets cannot be accurately modeled in 2D. The reason for this is, that the axial length of a machine normally consists of several magnets, but the 2D analysis assumes the geometry to continue as it is in the axial direction. Thus, the end-effects of the eddy-currents in each magnet are ignored in 2D analysis.

In 3D analysis the effect of the anisotropic resistivity was compared to the results calculated using isotropic resistivity. It was shown, that the eddy-current power results differ when anisotropic or isotropic resistivity is used. However, the difference was quite small. In different machine geometries, where the alternating field is a lot inclined to the magnetization direction, the anisotropy of resistivity should have a larger effect.

## ACKNOWLEDGMENT

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