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Mixed-Grade Pole Design for Permanent Magnet Synchronous Machines

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Abstract—**This paper introduces a design idea of a new kind of pole structure with different magnet grades used in one pole: "the Mixed-Grade Pole Design". This structure offers improved demagnetization protection and also brings potential cost savings by optimizing the use of dysprosium in Nd-Fe-B-permanent magnet material. A new demagnetization model with an exponential function is also introduced.**

The new design idea is compared with a traditional one-grade design by using finite element method electromagnetic simulations combined with the demagnetization model. Finally, the benefits of the new pole structure are discussed.

Index Terms—**Demagnetization, finite-element methods, permanent magnets, magnetic field modeling, mixed-grade pole.**

I. Introduction

MODERN large permanent magnet electric motors may have very large magnet poles. For practical and manufacturing reasons, a single magnet cannot be very big, thus a single pole in a large machine may consist of tens of magnets. If a pole is wide, one pole may have several magnets also in circumferential direction. This opens interesting possibilities in a machine construction.

Normally, a pole consists of one magnet material grade, which is selected as a compromise of flux production and demagnetization resistance. However, by using more than one magnet grades in one pole, several technical and economical benefits can be gained: a pole structure manufactured using several magnet material grades can have better resistance against irreversible demagnetization while giving more flux at the same time. This kind of "mixed-grade pole" design can also be cheaper than a single grade pole.

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Partial irreversible demagnetization of magnets in electrical machines has earlier been modeled with a two-line model in FEM environment by Kim *et al*. [1][2], Kang *et al.* [3][4] and Lee *et al.* [5]. They have used two different kinds of linear models. Different real hysteresis models have also been used to model demagnetization, for example by Rosu *et al*. [6]. Enokizono *et al.* [7] have used the theory of rotation magnetization to model magnetization of assembled anisotropic DC-motor magnets with FEM. Farooq *et al.* [8] have used a permeance network to model demagnetization. In their model they have assumed that the whole magnet has uniform magnetization, and thus uniform partial demagnetization. However, they suggest that the magnet should be divided in several sections, which might have different demagnetization. Boucherit *et al.* [9] have used the superposition theorem to model demagnetization. In their model, the air-gap flux density has two components: one for undemagnetized magnets and the other one is a fault component representing demagnetization. Ooshima *et al.* [10] have calculated analytically the maximum allowed stator current before demagnetization. Some demagnetization models have been compared by Ruoho *et al.* [11].

In this paper, a simple and fast model based on an exponent function is introduced to make the modeling of demagnetization fast and simple. This model allows performance calculations of electrical machine after some irreversible demagnetization. The benefits of this model are an easy implementation and a fast calculation. This model also allows an accurate modeling of real hysteresis curves of Nd-Fe-B magnet materials.

In this paper, a new "mixed-grade pole design" is introduced and simulated in the FEM environment using a new exponent function based demagnetization model.

II. Mixed-Grade Pole Design

A. Basic Idea

Nd-Fe-B-magnet material is manufactured in different grades. Some grades offer higher demagnetization resistance and higher working temperatures, while other grades offer higher remanence. Unfortunately, high remanence and high demagnetization resistance or intrinsic coercivity, cannot exist in the same magnet grade (Fig 1).

Magnet material grade in a synchronous machine should be selected to be able to resist the worst demagnetizing situation in the machine. The whole magnet material in the machine is traditionally selected according to the worst point in a magnet pole, which usually is in the leading or trailing edges. Other positions in the pole might have easier conditions. This means that if a magnet pole is constructed using several individual magnets, like large poles typically are, these individual magnets can be made of different magnet material grades, because each individual magnet has to endure different demagnetizing conditions. The basic idea of this "mixed-grade pole design" is that the magnetic properties of a permanent magnet in a permanent magnet pole structure can be a function of position.

Mohr and Odor have introduced a similar structure already in 1970s to resist armature reaction in ferrite magnet based DC motor [12]. They also introduced a manufacturing method suitable for manufacturing ferrite magnets with higher intrinsic coercivity in the other end.

If the mixed-grade pole design is used in large synchronous machines with Nd-Fe-B-magnets, there can also be economical benefits.

B. Technical Benefits

With mixed-grade pole design several technical benefits can be expected: demagnetization resistance and flux shape can be optimized. Eddy-current losses can also be degreased.

Demagnetization resistance can be improved by using a material with higher intrinsic coercivity in places, where demagnetization in the fault situations is the most probable. This normally means that a high intrinsic coercivity material would be used on the edges of a pole. In the middle of the pole, less intrinsic coercivity will be needed in many cases. Thus, a material with higher remanence could be used in the middle. With this structure, more sinusoidal flux density distribution from a pole is also possible.

The mixed-grade design requires that a pole is constructed using many individual magnets in circumferential direction. These individual magnets can be electrically insulated from each other and so the eddy-current losses in a pole structure can be minimized.

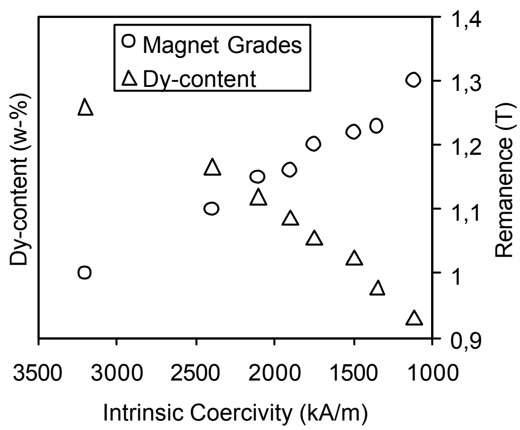

Fig. 1. Axially pressed magnet grades (circles) of a European manufacturer and the relative Dy-metal content of these magnet grades.

C. Economical Benefits

Nd-Fe-B-magnets contain rare earth metals, especially Neodymium (Nd) and Dysprosium (Dy) for some one third of their weight. Different Nd-Fe-B-grades can be manufactured by adjusting the relative amount of Nd and Dy. In high intrinsic coercivity magnets, which are the temperature resistant "motor grades", the quantity of Dy can be up to 10 % of weight or even more. In high remanence magnets, the content of Dy can be very low (Fig. 1).

At the end of 2006, the prices of Nd and Dy were as follows: Neodymium-metal 30 USD/kg and Dysprosium-metal 110 USD/kg. These prices have been lately increasing very rapidly: The average prices of Nd and Dy during 2002—2004 were around 7 USD/kg and 28 USD/kg, respectively. So the prices have quadrupled in just two years (Fig 2).

Dysprosium is much more expensive than Neodymium. This means that if the relative quantity of Dy can be decreased in a magnet, the price of the magnet will also be decreased. Because modern large PM machines can have up to several tons of magnet material, a saving in the amount of Dy can cause a significant cost reduction.

III. Exponential Function Demagnetization Model

Irreversible demagnetization of permanent magnets has been modeled with a two-line model by Kim *et al*. [1] [2]. Their model is simple, easy to implement and fast. Real hysteresis models are also used in FEM environment to model demagnetization [6]. The implementation of these models can be more difficult. With complex hysteresis models longer calculation times can also be expected. In some cases, especially, with Newton-Raphson iteration, complex hysteresis models can lead to convergence problems in FEM solution [13].

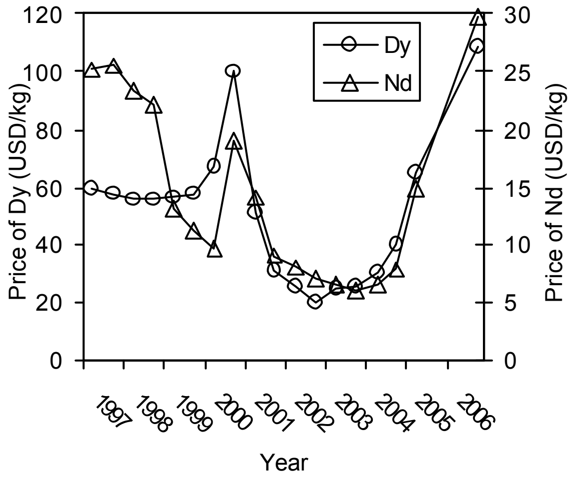

Fig. 2. Prices of Dy- and Nd-metals.

An exponent function model is used here to model irreversible demagnetization (Fig 3). The model is based on the following equation, describing the *HB*-curve of saturated Nd-Fe-B material in the first, second and partly in third quadrant:

$$B = B_r + \mu_0 \mu_r \cdot H - C \cdot e^{K_1 \cdot (K_2 + H)} \tag{1}$$

C is a constant needed for unit conversion. C = 1 T.

This model is easy to implement using remanence (B_r), slope of *HB*-curve (μ_r), intrinsic coercivity (${}_J H_c$) and one extra parameter K_1, which describes the sharpness of the knee in a curve (Fig 4). Parameter K_2 depends on the other quantities. Its value is obtained from equation:

$$K_2 = \frac{\ln\left[(B_r + (\mu_r - 1) \cdot \mu_0 \cdot {}_J H_c) \cdot \frac{1}{C} \right]}{K_1} - {}_J H_c \tag{2}$$

This exponent function model follows very accurately the real curve of NdFeB-material (Fig 5).

The simulations are made with a time-stepping FEM. The flux density at each time step is first calculated using a linear model for the magnet material, where only remanence and slope are defined. After the solution has converged, a working point for each element of permanent magnet material is checked. If the working point is too far on the negative *H*-axis when compared to the curve given by the exponent function, the remanence of that element is reduced to bring the working point back to the *B-H*-curve (Fig. 3). If there have been changes in the remanences of the elements during these checks, the flux density at the time step will be recalculated using the updated remanence values and checked again.

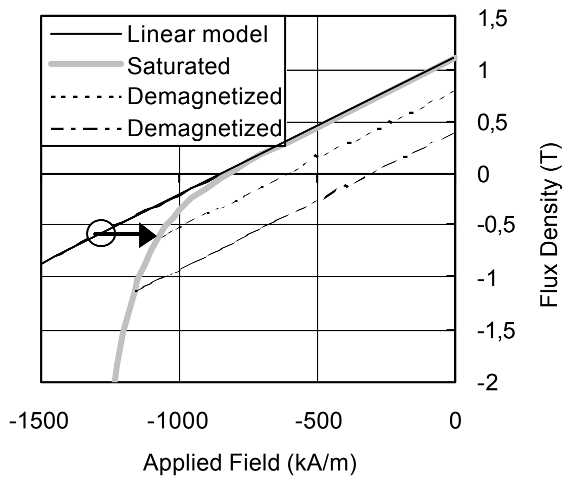

Fig. 3. Irreversible demagnetization of Nd-Fe-B-magnet modeled with the exponent function model. The working point (circle in figure), which is calculated using the linear model, is reduced to a curve described by the exponent function, if the working point is too far on the negative *H*-axis.

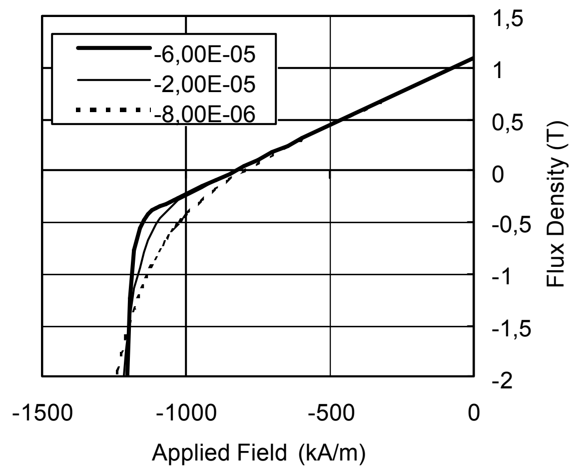

Fig. 4. The effect of parameter K_1.

IV. Modeling with an Example Machine

A. Example Machine

A six-pole salient pole synchronous machine was used to simulate the mixed-grade pole design. The same kind of machine was used by Rosu *et al*. [6]. The main parameters of the motor are presented in Table I.

The pole of the machine was constructed using four magnets in the circumferential direction (Fig 6). The FEM simulations were done using different magnet grades in different positions.

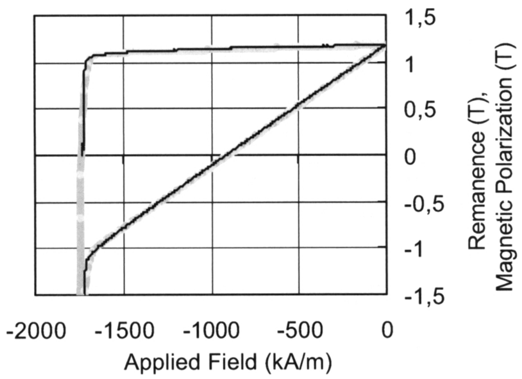

Fig. 5. Exponent function model (gray curves) compared with measured Nd-Fe-B-magnet curves (black curves).

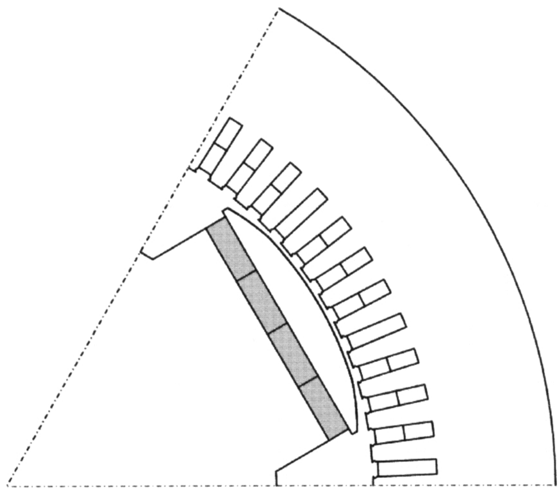

Fig. 6. Six pole machine with four magnets per pole.

B. FEM Modeling

The simulations were done using time-stepping based FEM using Newton-Raphson method as solver. First-order elements were used. There were 1818 elements and 937 nodes.

First the machine electromotive force (EMF) of the machine was calculated. After that a three-phase short circuit was modeled. The total demagnetization was then determined by calculating the EMF again.

The simulations were done using three different magnet grades. The magnet grades are described in Table II. The magnet temperatures were assumed to be 80°C.

C. Results

The results of calculations are described in Table III.

D. Discussion

The first row solution in Table III based totally on material "1" shows the highest EMF but after a 3-phase short circuit, the drop of EMF is 12 %. This is very high and means, that the first structure cannot be used.

The second row solution in Table III shows a quite high EMF, which drops only 2 % after the fault.

The third row solution based on material "3" has the lowest EMF in the beginning, but survives the fault with practically no drop in EMF.

TABLE I
MAIN PARAMETERS OF MODELED SIX POLE MACHINE

Parameter:	Value
Outer diameter of the stator	1200 mm
Air gap diameter	795 mm
Core length	1260 mm
Number of stator slots	72
Connection	Star
Rated voltage	690 V
Rated power	1.1 MW

TABLE II
ND-FE-B-MAGNET GRADES USED IN CALCULATIONS

Symbol	B_r in 20°C (T)	$_JH_c$ in 20 °C (kA/m)	B_r in 80°C (T)	$_JH_c$ in 80 °C (kA/m)
1	1.24	-1350	1.14	-800
2	1.22	-1500	1.13	-980
3	1.20	-1750	1.11	-1150

The fourth row solution, which is the first mixed-grade pole design in a Table III, shows the highest EMF after 3-phase short circuit. The starting EMF is only 2 % less than on the first row. This structure also survives the fault without demagnetization.

The last row solution is based on the magnet grades "1" and "3". After the fault, the EMF has dropped 6 %. An important thing to note concerning this pole structure is that this pole demagnetizes first from the central magnets made of material "1", which has the lowest intrinsic coercivity.

In this design case, the irreversible demagnetization of machine should be less than 5 % after a short circuit situation. This means that the first calculated structure cannot be used and the last one is barely tolerable. If the demagnetization tolerance of row two (based totally on material "2") in Table III is not satisfying, the traditional method in design work is to change the magnet grade to the next one having a greater intrinsic coercivity, like to the material on row three based totally on material "3". However, by using the mixed-grade pole design described on row four, the same demagnetization tolerance against a 3-phase short circuit can be achieved while having less reduction in EMF.

The solution on the row four is superior compared to the other solutions presented, because solution on row four has the highest EMF after the fault.

TABLE III
RESULTS

Pole Magnet Structure (using symbols of table II)	*EMF* (V)	*EMF* after 3-phase short circuit (V)	Demagne-tization
1-1-1-1	804	707	-12 %
2-2-2-2	794	777	-2.1 %
3-3-3-3	781	780	-0.1 %
3-2-2-3	788	787	-0.1 %
3-1-1-3	792	746	-5.8 %

Pole structure 1-1-1-1 means that all the magnets in the pole are manufactured using the magnet material. Pole structure 3-2-2-3 means, that the edges of the pole are made using magnet material grade “3” and the middle parts material “2”.

V. Conclusion

A new design idea, the mixed-grade pole design was described, and its technical and economical benefits were discussed. By using different magnet material grades in a single pole structure, the demagnetization resistance can be optimized while keeping the EMF as high as possible. This kind of mixed-grade pole design also minimizes the use of dysprosium in Nd-Fe-B-magnet, which will cause a cost reduction.

A new demagnetization model based on an exponential function was described and compared to measured hysteresis curve of a Nd-Fe-B-sample. The model was implemented in FEM analysis and used to simulate a 3-phase short circuit of an example machine. The new demagnetization model appeared to be easy to implement, fast in calculations and it followed the real demagnetization behavior of Nd-Fe-B-magnet the quite well.

A six-pole salient pole machine was used to simulate the mixed-grade pole design. The demagnetization performance of the machine was modeled. The performances of different pole structures based on different magnet grades were compared. A structure based on the mixed-grade pole design showed the best properties against demagnetization.

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