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Demagnetisation of Permanent Magnets in Electrical Machines

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Abstract

This paper describes how an electrical engineer should take into account the possibility of Permanent Magnet (PM) demagnetisation when designing a PM machine. Different modern PM materials and used magnet models both in parametric models and in Finite Element Method (FEM) models are shortly described. Demagnetisation models and hazardous situations in PM machines are discussed. Finally, the instructions how to check the design against the risk of demagnetisation are discussed.

Keywords

Permanent magnet, demagnetisation, permanent magnet machine

Introduction

A permanent magnet is an essential part of modern electrical machine, which means that the PM material should be modelled properly. A good model should describe accurately each possible working point in second and third quadrant of hysteresis plane.

In present models of a PM machine, the permanent magnet material is usually modelled with two parameters only: remanence (B_r) and relative permeability. In some cases, instead of remanence, the normal coercivity ($_BH_c$) of material is used [1]. These parameters lead to a linear model that does not take into account the possibility of demagnetisation. Normally this is not a problem because PM machines should be designed so that the risk of demagnetisation is avoided even in some hazard situations like short circuits. However, if behaviour of machine after demagnetisation needs to be modelled a more sophisticated PM model is required.

Modern PM materials include ferrites, Rare Earth material and different plastic bonded materials. Most of these materials except some plastic bonded materials show almost linear behaviour up to the demagnetisation limit. Even with these present linear materials the risk of demagnetisation should be studied in each design case separately.

1 Permanent Magnet Materials

Different permanent magnet materials used in present applications are described as follows. At the end of this chapter, the magnet materials are compared in Table 1.

1.1 AlNiCo-magnets

AlNiCo-magnet material is the oldest permanent magnet material still in use. The best features of the AlNiCo-materials are low temperature coefficients and very high Curie temperature [2]. However, a really low intrinsic coercivity ($_JH_c$) of AlNiCo-materials restricts the use of these materials in many applications. AlNiCo-materials show highly non-linear behaviour in the second quadrant of BH-plane, which makes the modelling quite difficult.

1.2 Hard Ferrites

Hard ferrite or ceramic magnets are the most important magnet materials commercially. The best features of ferrite materials are low cost and very high electrical resistivity [3]. However, because of relatively low B_r, these magnets are not normally used in high tech applications. Anisotropic hard ferrite materials have linear behaviour in normal temperatures.

1.3 SmCo-magnets

SmCo-magnets belong to Rare Earth magnets, like NdFeB-magnets. SmCo magnets have high remanence, high intrinsic coercivity, low temperature coefficients and high corrosion resistance. The drawbacks of SmCo-materials include high price depending on Co-price and in some applications also the electric conductivity.

There are two different SmCo materials: $SmCo_5$ and Sm_2Co_{17}. These materials differ mostly in magnetization behaviour. SmCo magnets have linear behaviour.

1.4 NdFeB-magnets

NdFeB-magnets belong to Rare Earth magnets. NdFeB-material is the most important PM material in large machine and generator applications. These magnets offer the highest possible remanence and depending on the grade, also very high intrinsic coercivity. However, the temperature coefficients are quite high and also the corrosion might be a problem for NdFeB-magnets. NdFeB-magnets do conduct electricity quite well, which might also be a problem. NdFeB-magnets have linear behaviour.

1.5 Bonded-magnets

Magnet material can be mixed to plastic or rubber material. With these methods, very special combinations of mechanic and magnetic properties can be achieved. The magnet material can be oriented to create anisotropic magnets with higher remanence. If the material is left unoriented, an isotropic material is created.

Bonded magnets do not conduct electricity and some very special shapes are possible by using plastic injection molding. Normally, the following permanent magnet materials are used to create bonded magnets: ferrite, SmCo, NdFeB and SmFeN. Some bonded magnets show linear behaviour, but in most cases the behaviour is somewhat non-linear.

Table 1. Comparation of Permanent Magnet Materials [4, p 69] [5]

Material	**Remanence B_r (T)**	**Intrinsic coercivity $_JH_c$ (kA/m)**	**Curie temperature (°C) [4, p 69][5]**	**Temperature coefficient of B_r (%/°C) [5]**	**Temperature coefficient of $_JH_c$ (%/°C) [5]**	**“Pros and cons” of magnet material**
AlNiCo	0.5…1.35	40…150	700…850	-0.01…-0.02	-0.02…-0.04	+ Low temperature coefficients - Very low intrinsic coercivity - non-linear behaviour
Hard Ferrites	0.15…0.43	150…350	450	-0.2	+0.3…+0.5	+ Low cost material + High electrical resistivity + Linear - Quite low B_r
SmCo	0.9…1.1	700…2400	500…850	-0.04	-0.2…-0.3	+ High magnetic properties + Linear - High cost
NdFeB	1.0…1.4	900…3200	310	-0.1	-0.4…-0.8	+ Highest magnetic properties + Linear - High temperature coefficients - Prone to corrosion
Bonded magnets	Note 1)	Note 1)	Note 1)	Note 1)	Note 1)	+ Complex shapes possible + Non-conductive - In many cases non-linear - Low magnetic properties

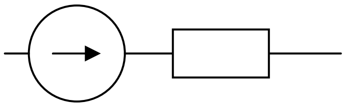
Note 1): Wide range based on the mixed magnet and plastic material

2 PM Models in Electrical machines

2.1 Linear parametric models

When making a magnetic circuit analysis by parametric model the magnet material is modelled simply by using a straight line in *BH*-plane. The straight line is normally defined by remanence (B_r), which is the intersection point of vertical B-axis, and with permeability μ_r, which is the slope of the straight line.

In parametric models, the magnet is modelled with a series connected flux source and reluctance (Figure 1).



$$l_m \cdot H_c \Rightarrow l_m \cdot \frac{B_r}{\mu_r \mu_0}$$

Figure 1. A reluctance model of PM

In these parametric models, the strength of flux source is usually defined as a product of normal coercivity $_BH_c$ and the magnet thickness l_m. Instead of that, a product of B_r divided by $\mu_r\mu_0$ and magnet thickness l_m should be used to avoid the possibility of confusions in case if the magnet has non-linear behaviour in second quadrant of *BH*-plane.

For example if material NEOREM 453a would be used in temperature 150°C, the use of normal coercivity $_BH_c$ in a parametric model source term would lead to an incorrect result because that material shows non-linear behaviour in 150°C (Figure 2).

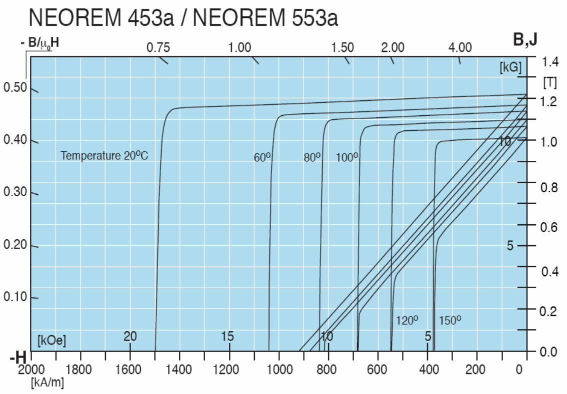


Figure 2. A set of hysteresis curves in second quadrant [6]

2.2 Magnet Models in FEM

In a finite element method, the magnet can be described with two possible methods:

- The element containing magnetic material can be a source of magnetic field itself causing an additional term to equation to be solved [7]
  (Second term in equation 1)

$$\nabla\times\frac{1}{\mu}\nabla\times\vec{A}-\nabla\times\frac{1}{\mu}\vec{B}_r=0 \qquad (1)$$

- The magnet can be described by a linear material of having constant μ and having a current sheet circulating B_r along the magnet edges

2.3 Linearisation of non-linear behaviour

Some magnet materials like AlNiCos and some bonded magnet materials show highly non-linear behaviour. The instructions how to treat these materials can be found in literature: [8] [4, pages: 85-97]
The basic idea is to find the worst working point with lowest field density inside the magnet and linearise the behaviour by using recoil permeability as a slope according to Figure 3.

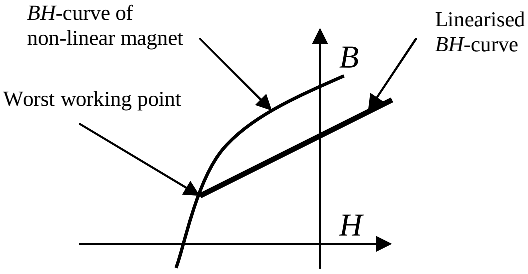


Figure 3: Linearisation of non-linear BH-curve

2.4 Use of linear models

Linear models of permanent magnet material can be used in electric motor analysis. However, special care has to be taken to make sure that the working point of the magnet never leaves the linear or linearised area of the *BH*-curve. This check can normally be done at the end of the analysis. The basics of this demagnetisation check will be described later in this paper.

3 Demagnetisation Models Used in Literature

Most demagnetisation models or hysteresis models are describing the non-linear multi-value behaviour of magnetic material in macroscopic level in all four quadrants of *BH*-plane. These models can be applied both to hard magnetic materials and soft magnetic materials simply by changing parameters. Most used models are Preisach model introduced as early as 1935 [9] and Stoner-Wolhfarth Model.

In literature, there are only several cases, where a demagnetisation model has been applied to electrical machines. Preisach-model is used for example by Rosu, Saitz and Arkkio [10] to model the demagnetisation of magnets in large synchronous motors. Stoner-Wohlfarth-model is used by Enokionzo, Takahashi and Kiyohara to model the magnetization and demagnetisation of radially oriented magnet rings [11]. Kang et.al. [12] have used an iterative approach to model demagnetisation of ferrite magnets. They had approximated the *BH*-curve with two lines.

4 Hazardous Situations Causing Risk of Demagnetisation

4.1 Basic reasons of irreversible demagnetisation

If the working point of permanent magnet material goes below the “knee”-point in *BH*-curve (Figure 4), the magnet will experience irreversible demagnetisation. This can be caused in electrical machines by the field caused by anchor reaction. As the *BH*-curve is a function of temperature, a temperature increase only can cause irreversible demagnetisation (Figure 5).

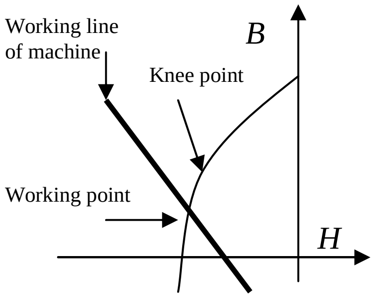


Figure 4: Working point below the knee of BH-curve will cause irreversible demagnetisation

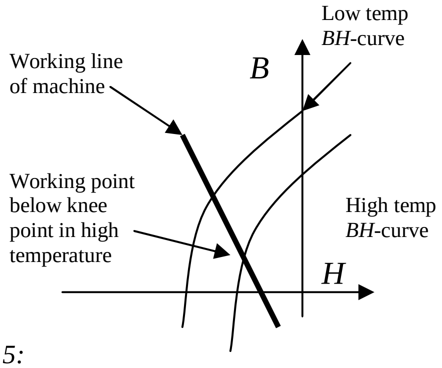


Figure 5:
High temperature causing demagnetisation

4.2 Temperature

High temperatures increase the risk of demagnetisation by shifting the whole *BH*-curve. High temperatures in machines can be caused by some hazard situation, by loss of cooling or by some non-usual loading. In fast rotating machines with narrow air gaps, the eddy currents can cause a rise of temperature in permanent magnets because most PM materials are conducting materials. There are several methods to eliminate these eddy currents is electrically conductive magnetic materials:

- By introducing a conductive material layer above the magnets [13, p 126]. In this case, the eddy current loss occurs in this conductive layer.
- By constructing the magnet from smaller pieces [13, p 128]

In some cases, it is also possible to use non-conductive magnet materials like ferrites or bonded magnets.

4.3 Line Starting

When line starting a permanent magnet machine with surface mounted magnets, the minimum field inside a magnetic material can be around –1 T before synchronisation. If the magnet material is at the same time in a higher temperature, a severe demagnetisation can happen. For example, the magnet material used in Figure 6 could survive such line starting in 100ºC without suffering irreversible demagnetisation. However, in 150ºC some irreversible demagnetisation in such line starting is expected.

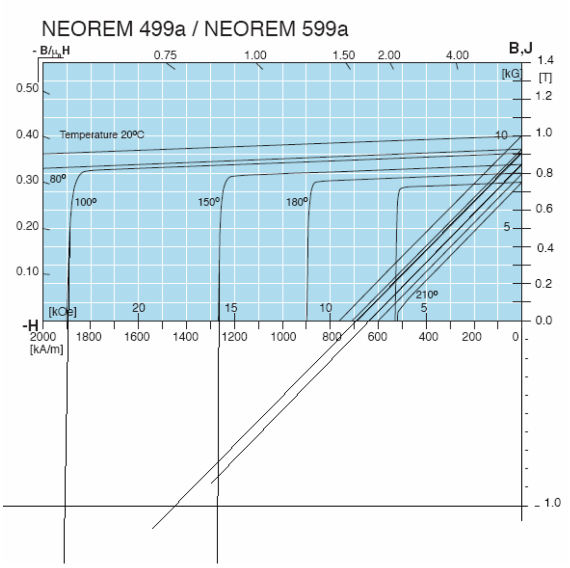


Figure 6: High performance magnet material in high opposite field in an elevated temperature [6]

4.4 Short Circuits

In different short circuits situations, similar opposite fields can be found inside a magnetic material than in line starting case. Rosu, Saitz and Arkkio [10] have simulated a two-phase short circuit and found a field of –1 T in corners of a permanent magnet. According to their publication, two-phase short circuits are more common and more dangerous from the demagnetisation point of view than one-phase or three-phase short circuits.

5 Checking the Risk of Demagnetisation in PM Machine Analysis

Each electrical machine design having permanent magnets should be checked for possible demagnetisation. Normally, only a simple check is needed at the end of analysis. The check is made accordingly:

- Find the highest possible temperature inside a magnet.
- Find the lowest possible field value inside a magnet given by FEM model. The lowest values of parametric model should be treated as average values inside a magnet.
- Using the *BH*-curve of the used magnet material, check that the point of the lowest field value is above the knee point.

Example:
Let the highest temperature inside a magnet be 150ºC, and the lowest field value in a magnet corner be –0.54 T. If the same magnet material as in Figure 6 is used, it can be seen that the working point would be above the knee point. Thus, no irreversible demagnetisation is expected.

If this check shows a risk of demagnetisation, there are several things to do:

- The magnet grade can be changed to a grade with higher intrinsic coercivity. At the same time the remanence normally decreases. This means that the magnet has to be thicker to produce the same flux with less remanence. This increase in magnet thickness raises the working point, which also helps against demagnetisation.
- The thermal design of the machine can be changed to reduce the maximum temperature.
- The air gap can be increased to reduce the anchor reaction. Of course, this reduced the machine performance.

When doing this check, it should be remembered that the magnetic values of permanent magnets have also a tolerances. The knee point is in the highest position when the magnet material has the highest remanence but the lowest intrinsic coercivity within the tolerance range. It should be kept in mind that the *BH*-curves for the magnet materials given by the manufacturers normally show typical values.

This simple check only reveals the risk of demagnetisation. If the machine performance after a demagnetisation is to be studied, a more sophisticated model allowing demagnetisation inside a magnet as a function of position should be used.

6 Conclusions

This paper gives an electrical engineer a reference how to check the electrical machine design against demagnetisation. Every electrical machine design should be checked against demagnetisation using the worst possible temperature and working point scenario. Normally, only a simple check is necessary to ensure the design.

To model the properties of the demagnetised machine in more detail, some sophisticated demagnetisation model should be used.

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