Nonlinear magnetization loss in sintered NdFeB magnet due to eddy current heat dissipation

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***Abstract*—NdFeB permanent magnets are widely used in high performance electrical machines. But, due to the increasing of magnets use in high speed applications, the magnets are subjected to eddy current losses that cannot be neglected. These losses can lead to local over-heating of the magnet and cause irreversible demagnetization. To study such effect, the Finite Element (FE) method can be used in order to describe with accuracy the local demagnetization loss of a permanent magnet (PM). The present work deals with the nonlinear modelling of a permanent magnet, implemented in a 3D FE model, that takes into account partial demagnetization effects and also temperature dependencies.**

***Index Terms*—Finite element analysis, permanent magnets, demagnetization, thermal dependent.**

I. INTRODUCTION

Sintered rare earth NdFeB magnets are widely used in industrial machine applications because of their high power density. As the electrical conductivity of these magnets is moderate the eddy current loss due to space and time harmonics cannot be neglected [1]. These losses can cause a significant heating of the PM and lead to an irreversible demagnetization, especially in the case of NdFeB magnets, which have high temperature coefficients of remnant magnetic flux density and coercive field. Therefore, an accurate behaviour law of the PM is needed in order to predict the eventual demagnetization loss.

For predicting magnetization loss different techniques have been discussed in the literature. Zhou *et al*. [2] presented a linearized demagnetization model of PM that takes into account the effect of temperature. Also nonlinear PM models have been proposed in [3] and [4] to highlight the effects of magnetization loss at a given temperature. Other works were interested in implementing hysteresis models [5] to describe the hysteretic behaviour of PM in electrical machines. Such approach is of interest if the PM behaviour law presents minor loops in the recoil curves that lead to additional losses.

In this communication, a nonlinear partial demagnetization loss model of PM is proposed. Coupled with the FE method the model takes into account the heating of PM induced by the eddy current loss. As illustration, a test device, with a NdFeB magnet, under different demagnetization conditions is studied.

II. PERMANENT MAGNET MODEL

A. Physical model

The demagnetization *B-H* curves of a PM for two temperatures are shown in Fig. 1. The initial magnetic state of the magnet is given by the intersection of the load line *L* and the initial temperature demagnetization curve. In Fig. 1, for the temperature T_1, the operating point is given by the point *A*. For a temperature $T_2>T_1$ the remnant flux density B_r and the coercivity H_c of the NdFeB magnet shifts towards the origin. In this case, the demagnetization curve presents a knee point and the demagnetization process can be separated into two distinct contributions:

- a reversible part (above the knee point *K*) where, if a demagnetization field H_b' is applied, the operating point of the magnet *B'* is determined by the intersection of the load line *L'* and the demagnetization curve *2*. If the demagnetization field is reduced to zero the operating point of the magnet will return to the operating point *B*.
- an irreversible part (below the knee point *K*) where, if a demagnetization field H_b'' is applied, the operating point of the magnet will fall at the point *B''* determined by the intersection of the load line *L''* and the curve 2. If the demagnetization field is decreased to zero, the operating point of the magnet is *C*. This point is determined by the intersection of the original load curve *L* and the recoil line 3 of the permanent magnet [3].

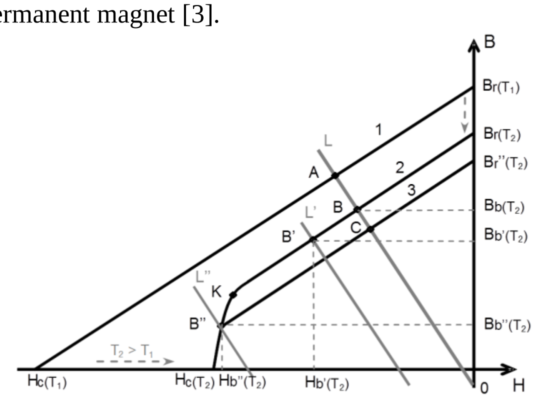

Fig. 1. Demagnetization process in a permanent magnet

B. Demagnetization behaviour law model

The proposed permanent magnet behaviour model is based on the Marrocco equation (1) that was originally used for the anhysteretic non-linear approximation of the soft magnetic materials behaviour law. In the same way, we use the Marrocco equation to fit the demagnetization curve of hard magnetic materials after being translated in the first *B-H* quadrant. For the numerical resolution, the curve is shifted again in the second quadrant [4].

$$H = \frac{B}{\mu_0}\left[\frac{B^{2\alpha}}{B^{2\alpha}+\tau}\left(c-\varepsilon\right)+\varepsilon\right] \qquad (1)$$

In this expression, H and B are respectively the magnetic field and magnetic flux density and α, ε, τ, c, are parameters that have to be determined by a fitting procedure with the experimental behaviour law.

It has been identified that parameters $\alpha(T,B_k)$, $\varepsilon(T,B_k)$, $c(T,B_k)$, $\tau(T,B_k)$ present a polynomial evolution versus the temperature T and the magnetic flux density B_k corresponding to the knee point. In addition, the model takes also into account the temperature dependence of B_r and H_c by using a polynomial evolution.

C. Numerical model

To investigate the demagnetization loss of a PM, a magneto-thermal modelling procedure is adopted according to Fig. 2. First, the permanent magnet state is calculated from an initialized uniform temperature (20°C) and the corresponding demagnetization curve. From this initial state, the eddy current losses and copper losses, also calculated by the electromagnetic FE model, are inserted in the FE thermal model to calculate locally the temperatures in the magnet. Next, the demagnetization curves associated to each element of the magnet are deduced from the temperature map in the magnet and inserted in the electromagnetic model that is solved again in order to obtain the new state of the magnet. This sequence is repeated until the temperature stabilizes.

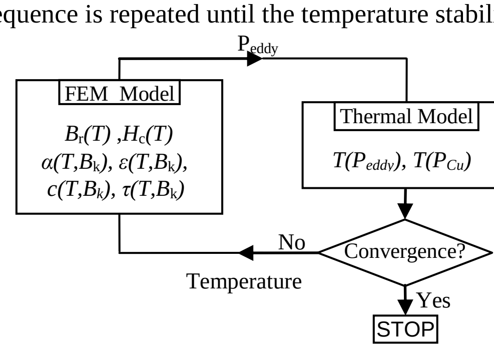

Fig. 2. Magneto-thermal sequence

III. Application

The test device used to illustrate the proposed approach is presented in Fig.3. A sintered NdFeB magnet (B_r=1.345T) is subjected to an alternating demagnetization field created by two coils connected in parallel and powered with a current of 4A at 200Hz. The steady state of the PM, in terms of temperature, is illustrated in Fig. 4. The eddy current loss and the temperature maps of the PM are given respectively in Fig. 4(a) and Fig. 4(b).

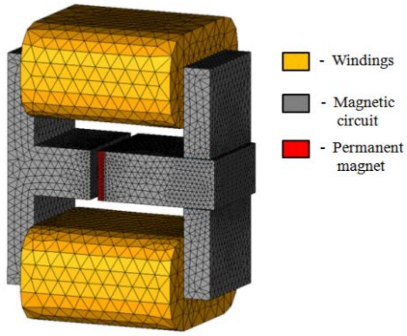

Fig. 3. FEM model of the closed circuit system

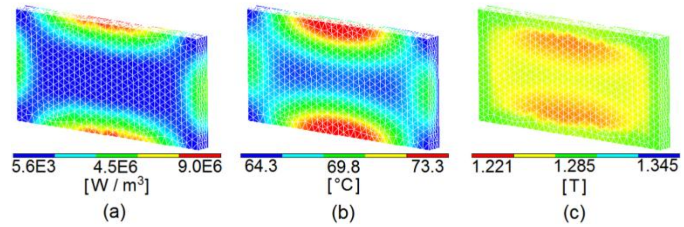

Fig. 4. Permanent magnet: (a) eddy current loss, (b) temperature, (c) Loss of remnant magnetic flux density

In Fig. 4(c) the local loss of remnant magnetic flux density of the PM is shown. It can be noticed that the whole magnet suffers from magnetization loss due to the temperature. However, the influence of the demagnetizing field led to a more pronounced magnetization loss in the centre of the magnet. The operating point (Fig.5) of an element in the centre of the PM highlights the proposed nonlinear magneto-thermal demagnetization model for the initial (blue curve) and the steady state (red curve).

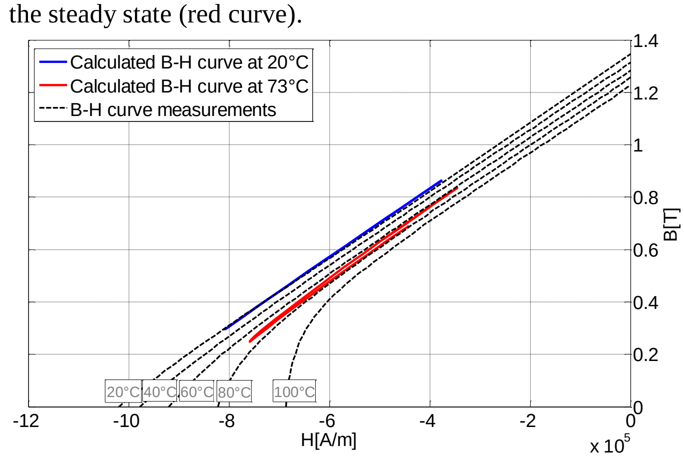

Fig. 5. Operating point of the PM in the center region

IV. Conclusion

The presented model for the magnetization loss in PM is based on a nonlinear behaviour law with variable parameters to account for the knee point and temperature dependence of the *B-H* curve. The approach has been illustrated by the study of a test device with an NdFeB magnet.

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