# Algebraic model for hysteresis and anisotropy of hard-magnetic materials modeled by finite element method

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**Many technologies in electrical engineering have benefited from the development of novel hard-magnetic material. However, so far there is no model which sufficiently describes a material's magnetization behavior in finite element analysis within acceptable computation time for dynamic problems, such as electrical machines. Therefore, simplified models are used which are often not capable of describing non-linearity, hysteresis and anisotropy. Particularly the simulation of dynamic magnetization processes is still challenging. Therefore, a parametric algebraic model is utilized, which is easily parametrized and models the physical behavior quite well. The model has been validated for soft-magnetic material on the TEAM Problem 32 and is compared in this paper for hard-magnetic material on pulsed field magnetometer measurements of high energy rare-earth permanent magnets.**

*Index Terms*—**Finite element analysis, magnetic analysis, magnetic anisotropy, magnetic hysteresis, hard-magnetic materials.**

## I. INTRODUCTION

**M**ODELLING hard-magnetic material for the finite element analysis is a complicated problem, because simultaneously modeling non-linearity, hysteresis and anisotropy are numerically challenging. Models for ferromagnetic magnetization processes are based on empirical, phenomenological, fundamental physics or energy-based approaches. Only easy parametrizable models with low additional computational effort are suited for commercial FEM software [1,2]. In addition, the challenge is to be suitable for soft as well as for hard magnetic material behavior. In this paper an empirical based magnetic material model, which was originally proposed for soft magnetic material, is adapted to suit for hard-magnetic materials.

## II. MAGNETIZATION MODEL

In [3] a parametric algebraic model (PAM) is proposed for the magnetization of soft magnetic material. As mathematical/empirical model it should basically also be suitable for hard magnetic material with a few adaptations. The equation of the PAM is given in (1) which consists of an anhysteretic term (incl. $p_{0-2}$) and a hysteretic term (incl. $p_{3-5}$). Each term can be replaced by other suitable functions, e.g. for the anhysteretic part in [4-5].

$$\vec{H}(\vec{B}, \dot{\vec{B}}, p_k) = \left( p_0 + p_1 |\vec{B}|^{2p_2} \right) \vec{B} + p_3 \dot{\vec{B}} + \frac{p_4 \dot{\vec{B}}}{\sqrt{p_5^2 + |\dot{\vec{B}}|^2}} \quad (1)$$

In [6] the model has been validated for soft magnetic material on the TEAM Problem 32. To overcome convergence problems raised by the magnetic material model, a differential reluctivity tensor is applied, such as in [7-8], to solve the finite element formulation of the magnetic vector potential.

## III. APPLICATION

Four rare-earth permanent magnet samples are tested: Vacodym764AP / Vacodym890AP (NdFeB), Vacomax170HR (SmCo5) and Vacomax262HR (Sm2Co17). The measuring procedures contain a magnetization measurement starting at virgin state and rises magnetizing field strength stepwise alternating in opposing directions, shown in Fig. 1. For low magnetizing field strengths the hard-magnetic materials are still of soft-magnetic nature. The remanence and coercivity increase with the applied magnetic field strength as a sigmoid function.

This publication is focused on the validation of an extended PAM for hard-magnetic material. Therefore, pulsed field magnetometer measurements are compared first to standard PAM with parameters fitted for the major loop, see Table I. The parameters can be assigned to material properties, for example the parameter $p_4$ to the coercivity. The parameter $p_3$ containing eddy current effects is fitted to zero for all samples.

TABLE I: PAM-parameters for pm-major-loops.

| Material | $p_0$ | $p_1$ | $p_2$ | $p_3$ | $p_4$ | $p_5$ |
|---|---|---|---|---|---|---|
| VACODYM764AP | 7.6 | 0.7 | 15.1 | 0 | 1457.8 | 4.0 |
| VACODYM890AP | 309.4 | 9.3 | 21.3 | 0 | 2474.1 | 9.8 |
| VACOMAX170HP | 1187 | 42301 | 78 | 0 | 2133 | 6 |
| VACOMAX262HP | 481.7 | 9.4 | 14.1 | 0 | 1905.8 | 4.3 |

One parameter set is not sufficient to describe the virgin magnetizing process. Due to a significant change of parameter values, an adapted parametrization for minor loops is necessary. In Fig. 2 this is done by a numerical fit. Alternatively, an adaptation of the major loop PAM parameters is conceivable, concerning the dependencies of the material properties.

## IV. CONCLUSION

The standard PAM requires corrections to fit the dynamic magnetization process of high-energy rare-earth permanent magnets. Additional terms and adapted parametrization are necessary to accurately model non-linearity, hysteresis and anisotropy. An extended PAM seems promising to suit for modeling magnetization of permanent magnets in finite element analysis.
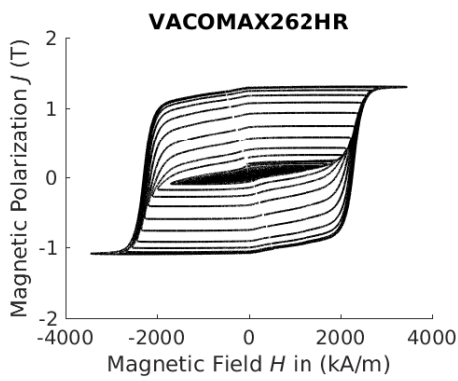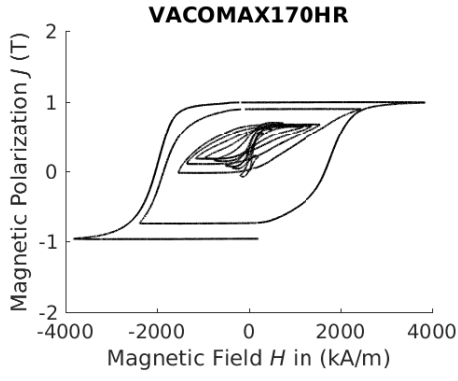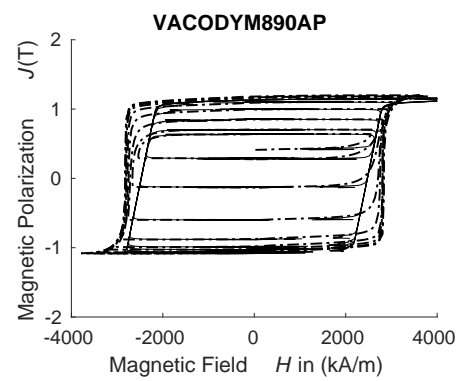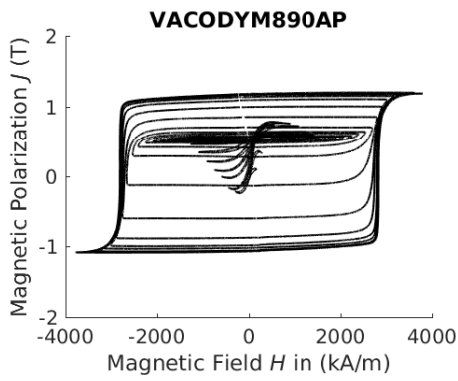
**VACODYM764AP**

**VACODYM890AP**

**VACOMAX170HR**

**VACOMAX262HR**

Fig. 1: Polarization as a function of applied field.

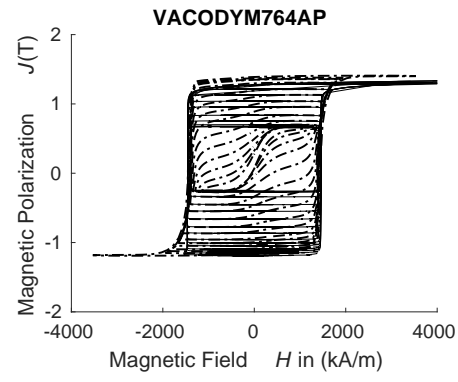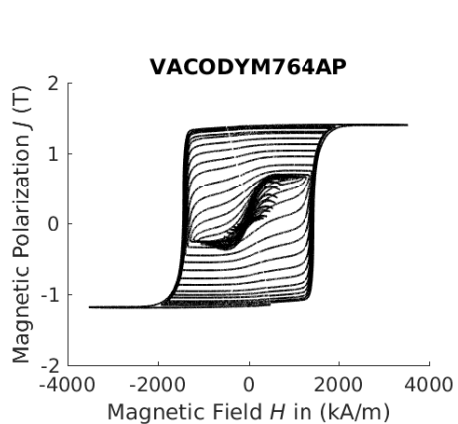**VACODYM764AP**

**VACODYM890AP**

Fig. 2: Measurements $(\cdot-)$ vs. PAM $(-)$ for magnetizing.

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