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Pulsed-Field Magnetometer Measurements and Pragmatic Hysteresis Modeling of Rare-Earth Permanent Magnets

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Rare-earth permanent magnets (REPMs) are central to the electromagnetic energy conversion process in permanent-magnet synchronous and flux-switching machines. To design the magnetic circuit and a magnetizing circuit for post-assembly magnetization, it is indispensable to describe the magnetization behavior of the REPMs accurately. Commonly, simplified models are used that are often not capable to replicate the non-linearity, magnetic hysteresis, and magnetic anisotropy. In this paper, four different REPMs are methodologically characterized by using a pulsed-field magnetometer. Their first-order return curves and magnetization behavior, starting from the virgin state, are recorded and used to parameterize and validate two different pragmatic hysteresis models.

***Index Terms*— Finite-element analysis (FEA), first-order return curves (FORCs), magnetic hysteresis, magnetic measurements, permanent magnets (PMs), rare-earth magnets.**

I. Introduction

MODELING of permanent magnets (PMs) for the finite-element analysis (FEA) of electrical machines is critical to the design of contemporary PM machines. However, due to the complex interplay of the non-linear and hysteretic magnetization behavior and the magnetic anisotropy, it is a complicated problem. Current models to describe the magnetization processes of PMs are based on empirical and phenomenological approaches, which only describe the major loop of the rare-earth PMs (REPMs). However, the magnetization state of the REPM strongly depends on the magnetization history. This requires to account for occurring minor loops or incompletely magnetized PMs. Efficient parametric models with low additional computational effort are suited for the FEA, i.e., [1]. These models are supposed to be parametrized without the need of time consuming and expensive measurements [2].

In this paper, pragmatic magnetization models based on empirical and phenomenological approaches are parametrized and validated by using in-depth pulsed-field magnetometer measurements of four different REPMs. Along with this, first-order return curves (FORCs) and the magnetization-state dependency are studied.

II. Material Samples and Measurement Setup

High-energy REPMs are characterized by high remanence and high coercivity. They are commonly composed of NdFeB or SmCo. In this paper, four different high-energy rare-earth PM samples are studied, which are listed in Table I. These samples are chosen to represent both low and high coercivity as well as nucleation- and pinning-type materials. Pulsed-field magnetometer measurements are conducted to study the material behavior subject to different magnetization states and to determine the parameters of two different hysteresis models.

TABLE I
Rare-Earth PM Samples

Name	Vacodym 764	Vacodym 890	Vacomax 170	Vacomax 262
Pressing direction	AP	AP	HR	HR
Code (IEC 60404-8-1)	305/135.5	210/263	170/120	143/175
Remanence B_r in T	1.30	1.11	1.01	1.19
Coercivity H_{cJ} in kA/m	1355	2625	1195	1750
Material	NdFeB	NdFeB	$SmCo_5$	Sm_2 Co_{17}
Magnetization type	nucleation	nucleation	nucleation	pinning
Shape	cylinder	cylinder	cylinder	block
Size in mm	15×5.5	10×10	10×10	$24 \times 17 \times 5$
Demagnetization coefficient	0.55	0.32	0.32	0.65

The characterizing quantities are the magnetic field strength H in A/m, the magnetic flux density B in T, and the magnetization M in A/m, i.e., magnetic polarization J in T, which are linked by

$$B = \mu H = \mu_0 \mu_r H = \mu_0 (H + M) = \mu_0 H + J. \qquad (1)$$

PM manufacturers usually provide the demagnetization curve in the second B/H-quadrant for different temperatures of a fully magnetized PM. These measurements are done either with a closed magnetic circuit (*IEC-60404-5*) or an open magnetic circuit (*IEC-V 42331*) approach. The closed-loop measurement is only able to provide impose a saturation field below saturation of the soft magnetic core material. This is below saturation of the PM. Due to this, the closed-loop structure, it is not capable to fully re-magnetize REPMs at any temperature. However, by heating up the material the complete hysteresis cycle can be measured. At lower temperatures, the results of tempered measurements must be converted by using the temperature coefficients, which are an additional source of error. The open-loop measurement is provided by an impulse magnetizer capable to fully magnetize any PM [3] with the difficulty of induced eddy currents [4]. However, reliable comparative measurements can be carried out as shown in [5].

The measuring device used as a basis in this paper is a pulsed-field magnetometer from Metis called HyMPulse.

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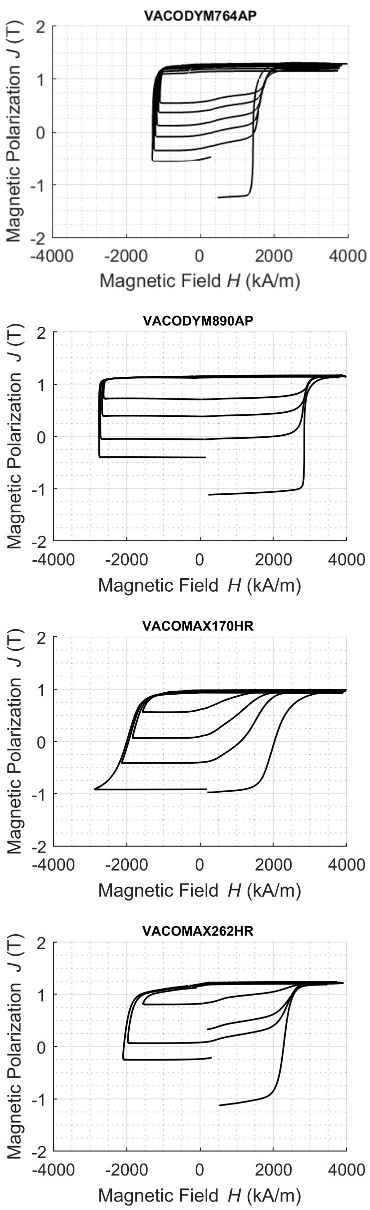

Fig. 1. FORCs for the different materials.

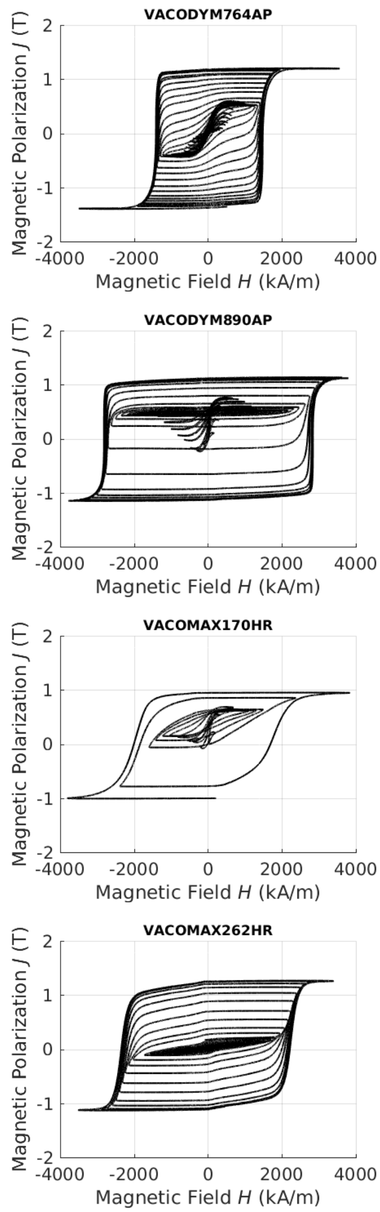

Fig. 2. Magnetization curves starting from the virgin state with increasing magnetic field strength.

FORCs are measured by applying an increasing demagnetizing field with full magnetization recovery in between (Fig. 1).

In addition, the PM magnetization process is characterized starting from the virgin magnetization state and then step by step increasing the magnetic field strength alternating in opposing directions (Fig. 2). It is apparent that the shape of the PM hysteresis curves strongly varies depending on the magnetic field amplitude. For the low magnetizing field, the PMs behave as a soft magnetic material. The remanence and coercivity increase non-linearly with the applied magnetic field (Fig. 3), while they decrease linearly with temperature.

III. Hysteresis and FORC Modeling

The direct use of measured characteristics represents a considerable twist in the modeling, because single measurements do not contain all mutual dependencies. The basic concept of algebraic magnetization models is the separation of the magnetization field, either in anhysteretic and hysteretic or ascending and descending components. Frequently used functions are, besides polynomials, the sigmoid functions [6]. Especially, the latter is first choice for both, to model the anhysteretic function [7], as well as to model the external hysteresis curve [8].

A simple pragmatic hysteresis model was proposed by Takacs [9] and DoÅ›piaÅ *et al.* [10]. The so-called $T(x)$ model (2) is suitable to represent the magnetization or the magnetic polarization as a function of the magnetic field or magnetic flux density

$$T(x) = p_1 \tanh(p_2(x \pm p_3)) \pm p_4$$

$$H(B) = \nu_0(B - J(B)) = \nu_0(B - T(B))$$

$$B(H) = \mu_0(H + M(H)) = \mu_0(H + T(H)). \tag{2}$$

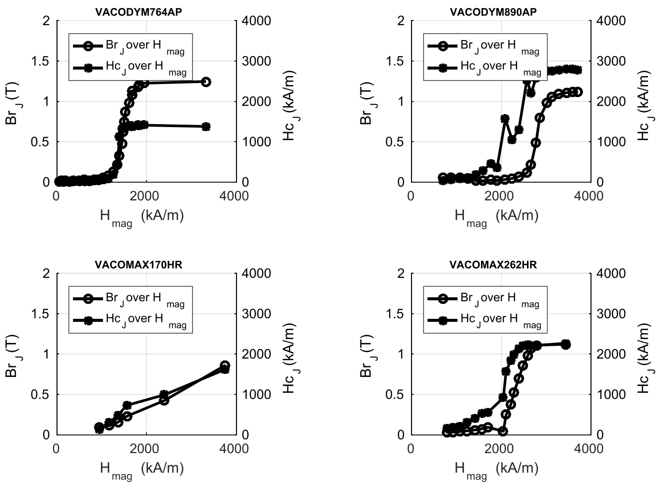

Fig. 3. Dependency of the coercivity and the remanence on the applied magnetic field.

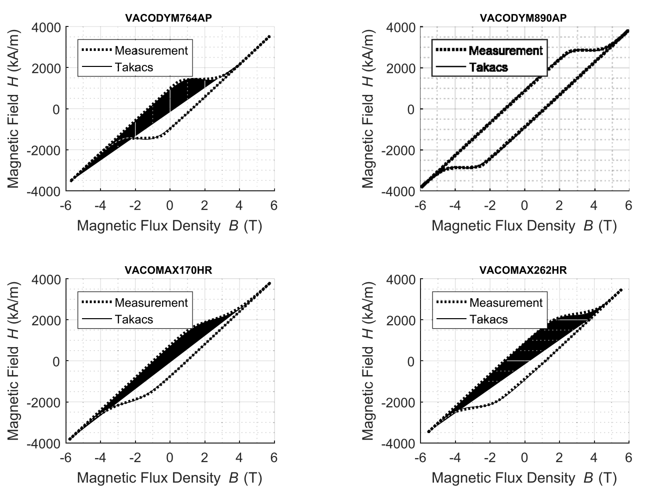

Fig. 4. Takacs model applied to major loops of REPMs.

TABLE II

PARAMETERS OF $H(B)$ TAKACS MODEL FOR MAJOR LOOPS OF REPMS

Material	p_1	p_2	p_3	p_4
VACODYM764AP	1.37	0.87	1.76	0
VACODYM890AP	1.15	0.99	3.5	0
VACOMAX170HR	1	0.71	2.54	0
VACOMAX262HR	1.2	0.78	2.8	0

TABLE III

ERROR IN HYSTERESIS AREA BETWEEN TAKACS AND MEASUREMENTS

Material	Area-measured	Area-T(x)	Area-Δ
VACODYM764AP	7.6339e6	7.6605e6	0.3476
VACODYM890AP	12.612e6	12.797e6	1.4171
VACOMAX170HR	8.1268e6	8.1154e6	-0.261
VACOMAX262HR	10.437e6	10.719e6	2.7047

In Fig. 4, the Takacs model is parametrized by using the major loops of the four REPMs. Table II contains the fitted parameters in case of $H(B)$. The parameter p_4 is always zero for a major loop. In Table III, the differences between the enclosed areas of the measurements and the Takacs model are depicted. Only a small absolute error occurs.

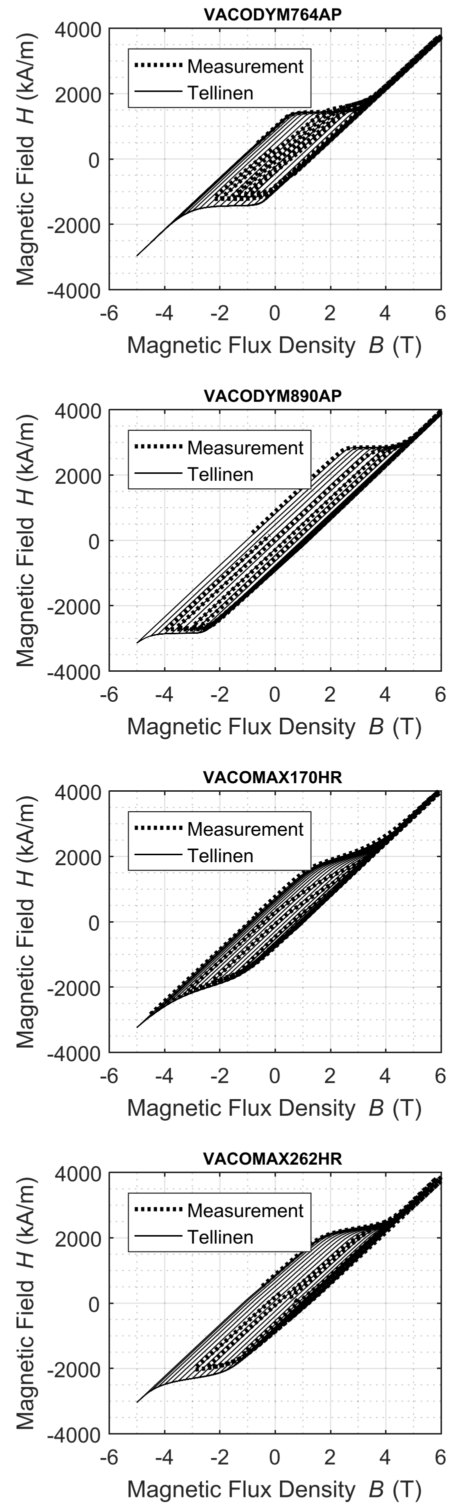

Fig. 5. Tellinen model applied to FORCs of rare-earth PM samples.

Another promising model was proposed by Tellinen [11] in 1998. The model has two advantages: 1) it is possible to start the calculations from both the field strength and the magnetic flux density and 2) its simplicity. The model is based on the limiting hysteresis cycle, which is used as the parametric data for the identification of the material. This implies that no extensive parameter identification is needed.

The combination of the convenient material identification and the quick implementation makes the model an interesting candidate for the finite-element implementation.

The hysteresis cycle is separated into an increasing $\lambda_i(H)$ and a decreasing branch $\lambda_d(H)$. The slope functions of the branches are $\rho_i(H)$, respectively, $\rho_d(H)$ and can easily be found by spline derivation. The differential permeability at any point can be determined by

$$\rho_B = \frac{dB}{dH} = \begin{cases} \rho_i(H) \cdot \dfrac{\lambda_d(H) - B}{\lambda_d(H) - \lambda_i(H)} & \text{for } dH > 0 \\ \rho_d(H) \cdot \dfrac{B - \lambda_i(H)}{\lambda_d(H) - \lambda_i(H)} & \text{for } dH < 0 \end{cases} \quad (3)$$

and the rate of change of the magnetic field can be calculated with

$$\frac{dH}{dt} = \begin{cases} \dfrac{dB/dt}{\mu_0 + \frac{\lambda_d(H)-B}{\lambda_d(H)-\lambda_i(H)} \cdot [\rho_i(H) - \mu_0]} & \text{for } dB/dt > 0 \\ \dfrac{dB/dt}{\mu_0 + \frac{B-\lambda_i(H)}{\lambda_d(H)-\lambda_i(H)} \cdot [\rho_d(H) - \mu_0]} & \text{for } dB/dt < 0. \end{cases} \quad (4)$$

It is apparent that the Tellinen model is suitable for finite-element formulations that use a magnetic vector potential formulation. Once the flux density is derived from the magnetic vector potential, also the magnetic field strength can be calculated by

$$H_{\text{new}} = H_{\text{old}} + \frac{dH}{dt} \cdot dt. \quad (5)$$

The Tellinen model is able to simulate minor loops, as well as FORCs (Fig. 5).

IV. Conclusion

Based on an in-depth metrological characterization, two different hysteresis models are studied. The Takacs model is suitable to replicate major loops of PMs with a slight absolute error. Furthermore, the model can also be extended for minor loops. The Tellinen model is capable to describe minor loops only with the knowledge from the major loops. While symmetric FORCs, such as those of VACODYM890AP, are well modelled, asymmetric FORCs, such as those of VACO-MAX170HR, cannot be reproduced correctly. Reasonable results with little computational effort are achieved.

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