Hysteresis Loss in NdFeB Permanent Magnets in a Permanent Magnet Synchronous Machine

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Abstract—Most permanent magnet (PM) loss studies consider only eddy current loss and neglect hysteresis. In this article, the hysteresis behavior of two NdFeB PM grades with different magnetic properties is assessed when applied in a PMSM. Data from vibrating sample magnetometer measurements and hysteresis modeling are used as a base. In addition to the main magnetic phase, the samples contained magnetic phases with reduced coercivity. Such phases may contribute to hysteresis losses in a PM material. A new model is introduced to simulate the hysteresis of rare-earth magnets of any geometric shape in the second and first quadrants of the intrinsic BH-plane. The magnetic field strength distribution in the PM material of an electrical motor is analyzed by two-dimensional finite-element method. The results are used as the input data for an analytical hysteresis model. The results indicate that the hysteresis loss resulting from the structural imperfections and geometry of the magnet may introduce a considerable loss in NdFeB PMs applied in rotating electrical machines.

Index Terms—Electric machines, loss measurement, magnetic field measurement, magnetic hysteresis, magnetic losses, magnetic materials, neodymium magnets, permanent magnet (PM) machines, permanent magnets (PM).

I. INTRODUCTION

PERMANENT magnet (PM) rotating electrical machines are developed intensively to meet the energy-efficiency improvement requirements. The rare-earth (RE) PMs (e.g., SmCo and NdFeB) enable PM electrical machine designs with superior efficiency and power or torque density [1].

The design of a high-efficiency PM electrical machine requires detailed analysis of possible loss components. In addition, the PM material itself is prone to losses that are difficult to evaluate precisely. Usually only eddy-current losses are evaluated in magnets during the typical design routine of PM-based electrical machine. This approach is based on thinking that in ideal PMs no hysteresis losses can take place. This is, however, not the case with real PMs and hysteresis losses can take place in them. Analytical and Finite Element (FE) methods estimating the PM eddy current loss are frequently discussed in the literature [2].

Several studies, however, report that, in addition to eddy current loss, the possibility for hysteresis loss must be analyzed in a real PM material, if it is used in a rotating electrical machine [3]–[8]. The alternating current (ac) magnetic field losses in Nd-based magnets are measured in [3] and [4] with nearly similar devices. Initially fully polarized PM samples are placed in a gapless magnetic circuit and the measured losses are separated to eddy current loss and hysteresis loss by the two-frequency method. The results indicate that in some normal-operation modes considerable amounts of hysteresis loss can be present. The measured data of PM loss only under ac fields in [3] are further used in the postprocessing of the FE calculated magnetic flux density distribution in PMs of a rotor-surface-magnet PM synchronous machine (PMSM). The calculated PM hysteresis loss is more than double the value of the eddy current loss. The calculation procedure in [3] ignores the effect of the demagnetizing field to the hysteresis loss in actual machine. In practice, the working point of a PM (applied in a machine) in the BH-plane has an extra self-demagnetization field resulting from the air gap and noninfinite permeability of the electric steel, which shift operating point deeper in the second quadrant of the BH-plane [9]. Measurement results with similar measurement device in [4] clearly indicate that the hysteresis loss in PM is significantly mitigated if negative direct current field is acting at the PM sample. Thus, the loss estimation procedure in [3] is not suitable for investigation of the hysteresis loss in electrical machines having the air gap as a natural demagnetization factor. It overestimates the PM hysteresis loss.

A general discussion on the PM hysteresis loss in sintered NdFeB magnets is provided in [5]. The measured data in [5] are limited by several recoil loops. The loops clearly depict that the formation of considerable hysteresis loops is possible in
Nd-based PMs in the normal operation of some RE PM machines.

A high-accuracy measurement system based on the vibrating sample magnetometer (VSM) is used to study the hysteresis behavior of three PM grades (NdFeB, SmCo, and Ferrite) in [6]. The calculated hysteresis loss in NdFeB PMs of the rotor-surface-magnet PMSM with external rotor topology is up to 1.4% of the studied machine’s output power. The limited measured data, the measurement temperature of 23°C, and the inappropriate treatment of the VSM output make the results in [6] questionable from the rotating electrical machinery point of view, i.e., the methodology in [6] may overestimate the actual hysteresis loss in PM motors.

Detailed investigations of the hysteresis loss in ferrite PMs are reported in [7], [8] via VSM measurements for four distinct grades, in total. The hysteresis behavior of ferrite magnets is simulated with a static history dependent hysteresis model (HDHM) and the total hysteresis loss is calculated in the PMs of two different PMSM designs. The results in [7], [8] show that significant hysteresis loss is possible also in ferrite PMs under operation conditions that regularly move back and forth between the second and the first quadrant of the $BH$-plane. The relatively small coercivity of ferrite PMs restricts the maximum possible armature reaction in the machine to avoid irreversible demagnetization. Therefore, only a small volume of ferrite magnets may be subject to considerable hysteresis loss. The studies [7], [8] are limited to ferrite magnets.

Based on our best knowledge, there are no accurate studies of the hysteresis loss phenomenon in NdFeB magnets of PM electrical machines. The geometrical and magnetic properties of RE magnets make this type of PM vulnerable to hysteresis loss in the rotating electrical machinery [8].

The rest of this article is organized as follows. Section II describes the possible origin of the hysteresis loss in Nd-based PMs, the measurement procedure, and the analytical modeling principle. The hysteresis loss is estimated analytically using FE estimated field-strength behavior in a PMSM with outer rotor topology and rotor surface magnets in Section III. Section IV discusses the results. Section V concludes the article.

II. METHODS

A. Origin of the Hysteresis Loss in NdFeB PMs

Hysteresis theory is the basic theory for the magnetic materials [10]. The relative permeability of practical NdFeB magnets $\mu_r \approx 1.01$–1.05 [10] differs from the relative permeability of vacuum. This is an indication of a fact that there are some magnetically soft phases in the material also enabling hysteresis in a PM sample. Numerous studies report that, in addition to the Nd$_2$Fe$_14$B main hard magnetic phase, an NdFeB magnet may contain magnetic regions with clearly lower coercivities [4], [10]–[17]. These regions may be located either on the surface or inside of the PM volume.

PM’s surface defects are studied and discussed in [4], [10]–[12]. The analysis in [4], [10] refers to the oxidation as the origin for reduced-coercivity magnetic phases on PM. The surface oxidation of an NdFeB magnet results in the formation of hexagonal Nd$_2$O$_3$ and $\alpha$-Fe magnetic phases with coercivities in the range of 50–200 kA/m (at ambient temperature) and a depth of around 10 nm at the surface of NdFeB grains [10]. The demagnetization of a NdFeB magnet is governed by the nucleation mechanism, which promotes the reversal of the surface layer of a PM (typical thickness 10–20 $\mu$m) [4], [10]. The study [4] estimates that the coercivity of the magnetic phases on the surface of the Nd PMs is only around 11%–35% of the coercivity of the main hard magnetic phase at the temperature range of 22–180°C. The Kerr microscopy images (by Evico Magnetics GmbH) in [4] support the assumption about the reduced coercivity of the magnetic phases on the surface, i.e., surface-located grains of initially fully polarized PM sample experience significant irreversible demagnetization under demagnetizing magnetic field strengths notably smaller than the intrinsic coercivity of the main hard magnetic phase.

Studies [11], [12] refer to the machining stresses on the damaged layer on the surface of NdFeB PMs. The cutting and grinding process of a bulk magnet removes part of Nd-rich phase volumes from the surface-located grains and as a result the magnetic interaction between the grains on the surface increases. The nucleation coercivity mechanism of NdFeB PM promotes the polarity reversal in the surface layer within the depth of the mean grain diameter. The measured main $BH$-curves demonstrate the presence of the magnetic phases with coercivities 13%–33% of the coercivity of the main hard magnetic phase in [11], and 31% in [12]. Studies [11], [12] demonstrate that sample heat treatment with temperature exceeding the melting point of the Nd-rich phase and the formation of a magnetic-insulating layer on the surface reduces the share of the magnetic phases with degraded coercivity. Nevertheless, a sample ideally consisting of just one main hard magnetic phase has never been demonstrated in practice. There are always some defects in a real PM material resulting in a relative permeability higher than unity which demonstrates the nonperfect nature of practical PM materials.

Reduced coercivity magnetic phases may be also located in the bulk volume of a magnet. The presence of $\alpha$-Fe, FeB, and Nd$_2$O$_3$ magnetic phases have been reported inside NdFeB magnets [13]–[16]. The Nd-rich phase has the strongest effect on the coercivity of the PM, and it is usually nonhomogeneous with respect to thickness and chemical composition [13], [14]. Therefore, a general analysis of the volumetric defects in sintered NdFeB magnet is difficult. Studies [15], [17] investigate the magnetic behavior of sintered NdFeB magnets with sophisticated analysis of the measured first-order reversal curves (FORCs). The studies provide evidence that the magnetic phases with coercivities around 40% to 80% of expected PM coercivity may originate from either Nd$_f$ site (see e.g., Fig. 4 in [15]) or Nd-rich phase, and, therefore, these phases may be an intrinsic property of a sintered NdFeB magnet. The estimated coercivities of these phases are in the range of 374–636 kA/m (at room temperature), and, therefore, they unlikely originate from the oxidation or machining of the PM surface [15].

Based on the results discussed above, this article assumes the following: 1) Magnetic phases with coercivities around 11%–35% of the coercivity of the main magnetic phase are located on the surface of the sample. These phases originate...
either from the surface layer oxidation or from the machining process. 2) Magnetic phases with coercivities 40%–80% of the main magnetic phase coercivity are located in the bulk volume of a PM sample. These phases may be associated with the Nd-rich layer or Nd-f site, and they are an internal property of an Nd PM.

B. Measurement Setup and Data Treatment

The test installation comprises a physical-properties-measurement system with up to 14 Tesla superconducting magnets, P525 VSM, and a data acquisition system by Quantum Design. The intrinsic properties of PM, i.e., polarization \( J \) with respect to the intrinsic field strength \( H \), are obtained from VSM-measured data according to the procedure introduced in [18].

The VSM measures the sum of the responses of all magnetic phases accumulated within one measurement signal of the sample. Reduced-coercivity magnetic phases may have a distinct contribution and the magnetic properties of the magnets can have certain discrepancy even in the samples from the same batch. Thus, several samples of the same grade must be measured and analyzed to get a more accurate picture of the distribution of the magnetic phases in a PM grade. The studied NdFeB PMs are uncoated samples of 512a and 793a grades supplied by Neorem Oy. The dimensions of the samples are \( 3 \times 3 \times 2(\text{M} \uparrow \uparrow), 3 \times 3 \times 3.8(\text{M} \uparrow \uparrow), 2 \times 2 \times 1.7(\text{M} \uparrow \uparrow), 2 \times 2 \times 3(\text{M} \uparrow \uparrow), 3 \times 3 \times 0.5(\text{M} \uparrow \uparrow), 3 \times 3 \times 1(\text{M} \uparrow \uparrow), 2 \times 2 \times 0.7(\text{M} \uparrow \uparrow) \text{ mm}^3 \) for 512a grade and \( 3 \times 3 \times 2(\text{M} \uparrow \uparrow), 3 \times 3 \times 0.5(\text{M} \uparrow \uparrow), 3 \times 3 \times 1(\text{M} \uparrow \uparrow), 2 \times 2 \times 0.7(\text{M} \uparrow \uparrow) \text{ mm}^3 \) for 793a grade, respectively. The measurement temperature is set to 80°C, which may be a representative PM operating temperature in an electrical machine [9]. The measurement sequence included the measurement of the main demagnetization curves. The distribution of the magnetic phases is analyzed with the following optimization function which was derived from the original idea published in [19]:

\[
J(H) = \sum_{i=1}^{3} V_i \cdot \left( J_i \cdot \tanh(\lambda_i \cdot (H + H_{c,J,i})) + \mu_0 \cdot \xi \cdot (H + C_i) \right),
\]

where \( V_i, J_i, \lambda_i, H_{c,J,i} \), are the relative volume, remanent polarization, steepness coefficient, and intrinsic coercivity of the \( i \)-th magnetic phase of the sample, \( C_i = 0 \) is the parameter needed for the analysis. The parameter \( \xi \) is small in practice, and it is referred as a measurement error e.g., in [20]. The measured and fitted with (1) main demagnetization curves are depicted in Fig. 1. The distributions of the magnetic phases estimated with (1) for the samples studied are depicted in Fig. 2.

The data in Fig. 2 demonstrate the same trend for each measured sample. The main magnetic phase 1 with the highest coercivity \( H_{c,J,1} \) has the dominant volumetric share \( V_1 \), whereas the shares \( V_2 \) and \( V_3 \) of the magnetic phases with reduced coercivities \( H_{c,J,2} \) and \( H_{c,J,3} \) are markedly lower. The magnetic phases with reduced coercivities have \( H_{c,J,2} = (0.23–0.31)H_{c,J,1}, H_{c,J,3} = (0.38–0.61)H_{c,J,1} \) for 512a grade, and \( H_{c,J,2} = (0.16–0.31)H_{c,J,1}, H_{c,J,3} = (0.55–0.68)H_{c,J,1} \) for 793a grade, respectively.

The distributions obtained for \( H_{c,J,2} \) and \( H_{c,J,3} \) are well in the ranges of the results in [4], [10]–[17], as it was discussed earlier. The median values for the relative volumes of volume-located magnetic phases with the reduced coercivities \( V_2 = 0.029 \) and \( V_3 = 0.075 \) are estimated from data in Fig. 2 for the grades 512a.
and 793a, respectively. The height of the damaged layer on the surface of the \(i\)th-sample \(h_{\text{layer},i}\) may be calculated from the geometric dimensions of the sample and the data in Fig. 2 as

\[
h_{\text{layer},i} = V_{2,i} \cdot (S/V)^{-1}.
\]

The calculated median values are \(h_{\text{layer}} = 9.48\ \mu m\) and \(h_{\text{layer}} = 6.68\ \mu m\) for 512a and 793a grades, respectively. The grain size of the commercial NdFeB magnets is reported in the range of 5–15 \(\mu m\) [4], [11], [13], [21]–[23]. Therefore, the statistically estimated median heights of the damaged surface layer are physically feasible, and they are used as reference values in the modeling of the hysteresis loss phenomenon in the PM magnetic poles described further.

**C. Modeling of the Hysteresis Loss in PMs**

The measured main demagnetization curves of the samples in Fig. 1 are formed by several magnetic phases with different properties. In addition, the surface-located layer of the magnetic phases with reduced coercivity causes the main demagnetization curve to depend on the size of a magnet. There are several modeling concepts to simulate the PM hysteresis. Detailed reviews may be found in [7], [8], [24]. Most hysteresis models are developed for the materials consisting of one magnetic phase, and, thus, require modification for the case studied.

The modeling concept in this article develops further the simulation principle introduced in [7], [8]. The hysteresis behavior of an NdFeB PM is represented by artificial “hard” and “soft” magnetic phases acting simultaneously. The “soft” magnetic phase is actually hard in its nature [25], but it is called “soft” just because of the presence of the magnetic phase with clearly higher coercivity. The “hard” magnetic phase represents the hysteresis behavior of the volume-located magnetic phases, i.e., phase 1 and phase 3. The “soft” magnetic phase (i.e., phase 2) represents the contribution of the surface-located magnetic phases with reduced coercivity. The hysteresis behavior of each artificial magnetic phase is simulated by the static version of HDHM [26]. The HDHM may be substituted with other hysteresis modeling alternatives that obey the most relevant Madelung rules for magnetic hysteresis [7], [8].

The HDHM concept enables the simulation of a part of a material’s \(JH\)-curve, which considerably reduces the measurement data needed. The procedure for building the model and parameter identification is presented for 512a grade as an example:

1) Step 1: Creation of the main loops for the “hard” and “soft” magnetic phases

The measurement data is acquired from the \(3 \times 3 \times 2\) mm\(^3\) PM sample in second and first quadrants of the intrinsic \(BH\)-plane at \(80^\circ C\). The simulation region is constrained within \((H_{\lim,1}, H_{\lim,2})\) by the part of the main demagnetization curve \(\text{desc}(H)\) and FORC \(\text{acs}(H)\), as it is depicted in Fig. 3. The basic principle of HDHM is shown in Fig. 4. The magnetic properties of the phases are estimated with (1), where the relative volumes of the magnetic phases with reduced coercivity \(V_2\) and \(V_3\) are no more optimization variables. The values of \(V_3\) are equal to the median values estimated in the previous subsection. The value of \(V_2\) is estimated from the sample geometry with (2) and the calculated median values \(h_{\text{layer}}\) for each PM grade, respectively. The descending main branch of each magnetic phase must follow the return-point-memory rule, i.e.,

\[
\begin{align*}
J_{\text{acs},i}(H_{\lim,1}) &= J_{\text{des},i}(H_{\lim,1}) \\
J_{\text{acs},i}(H_{\lim,2}) &= J_{\text{des},i}(H_{\lim,2})
\end{align*}
\]

The condition (3) makes \(H_{c,i}, \lambda, i\) to be the only optimization variables in (1) when ascending main curves are estimated.
whereas the other parameters are calculated as

$$C_i = \frac{Z_1 \cdot y_i(H_{\text{lim},2}) - Z_2 \cdot y_i(H_{\text{lim},1}) + V_i \cdot (M_1 Z_2 - M_2 Z_1)}{V_i \cdot (Z_1 - Z_2)} \quad (4)$$

$$J_i = \frac{y_i(H_{\text{lim},1}) - V_i \cdot M_1}{V_i \cdot Z_1} - \frac{Z_1 \cdot y_i(H_{\text{lim},2}) - Z_2 \cdot y_i(H_{\text{lim},1}) + V_i \cdot M_1 \cdot Z_2 - V_i \cdot M_2 \cdot Z_1}{V_i \cdot (Z_1 - Z_2)} \quad (5)$$

$$y_i(H) = V_i \cdot (1 \cdot \tanh(\lambda_i \cdot (H + H_{c,i})) + \mu_0 \cdot \xi \cdot H) \quad (6)$$

$$Z_1 = \tanh(\lambda_i \cdot (H_{\text{lim},1} + H_{c,i})) \quad (7)$$

$$Z_2 = \tanh(\lambda_i \cdot (H_{\text{lim},2} + H_{c,i})) \quad (7)$$

$$M_1 = \mu_0 \cdot \xi \cdot H_{\text{lim},1} \quad (8)$$

$$M_2 = \mu_0 \cdot \xi \cdot H_{\text{lim},2} \quad (8)$$

The data estimated with (1), (4)–(8) are depicted in Tables I–II for 512a and 793a grades, respectively.

2) Step 2. Parameter identification procedure of HDHM for artificial “hard” and “soft” magnetic phases.

The details of HDHM may be found, e.g., in [7], [26] with concise discussions and application examples, therefore, the modeling concept is discussed only briefly in this article. The $n$th order reversal curve is estimated from the $(n - 1)$th and $(n - 2)$th reversal curves, which form the current outer loop and are always known from the previous magnetization history. The current reversal curve is constructed with the gap $\Delta H(J) [8]$

$$\Delta H(J) = \frac{\Delta H_{\text{rev}}(J_{\text{RC}})}{\Delta J_{\text{rev}}} \cdot \left[1 - (b - d) \cdot \frac{\Delta J(J)}{\Delta J_{\text{rev}}} + d \right]$$

$$+ (H_{\text{asc}}(J) - H_{\text{des}}(J)) \cdot \left( (b - d) \cdot \frac{\Delta J(J)}{\Delta J_{\text{rev}}} + d \right) \quad (9)$$

where $J_{\text{RC}}$ is the polarization value at the reversal point, $H_{\text{asc}}(J)$ and $H_{\text{des}}(J)$ describe the ascending and descending branches of the current outer loop, and $\Delta H_{\text{rev}}(J_{\text{RC}}) = H_{\text{asc}}(J_{\text{RC}}) - H_{\text{des}}(J_{\text{RC}})$. Fig. 4 demonstrates the calculation principle for $\Delta J(J)$ and $\Delta J_{\text{rev}}$ for the third ORCs as an example. The behavior of the constructed reversal curve depends on its starting point at the current outer loop. It is described by a set of coefficients $\alpha(\beta) > 0, 0 \geq d(\beta) \geq 1$ that are estimated based on the measured hysteresis behavior of the PM. The parameter $\beta$ depends on $\Delta J_{\text{rev}}$ and the height of the current outer loop $\Delta J_{\text{out}}$:

$$\beta = \frac{\Delta J_{\text{rev}}}{\Delta J_{\text{out}}} \quad (10)$$

Parameter identification procedure was conducted for the ascending and descending curves separately based on the FORCs and several recoil loops, which are measured in the region of interest. Fig. 5 depicts the coefficients estimated for the model. Figs. 6 and 7 demonstrate a comparison of the measured and model-simulated results for 512a grade and 793a grade, respectively. The model-estimated hysteresis behavior of magnets is
Fig. 6. Comparison of the measured (solid red line) and model-simulated (dashed line) hysteresis behavior for $3 \times 3 \times 2(M^{↑↑})$ PM sample of grade 512a at 80°C. The main $JH$-curve is depicted with circle markers. (a) Set of FORCs. (b) Hysteresis behavior of PM when the external field is strong enough to move the operating point of PM from the second to the first quadrant of intrinsic $JH$-plane and backwards, respectively. (c) Hysteresis behavior of PM in the second quadrant of the intrinsic $JH$-plane.

used to evaluate the amount of the hysteresis loss in PMs of an electrical machine.

III. RESULTS

A power-dense tooth-coil-winding rotor-surface-magnet PMSM with an outer rotor was studied in terms of hysteresis losses. The design topology chosen is reported to have a high magnetic field strength variation in the PMs because of the rotor-surface PMs, tooth-coil-w windings, and the relatively wide slot openings [8], Table III. The PMSM topology is depicted in Fig. 8 for the motor design with 793a grade as an example. Each PM is sliced with $w_1 = 1$ plane parallel to $lh$-plane and $w_2 = 32$ planes parallel to $lw$-plane, i.e., segmented into 66 equal pieces with dimensions $20 \times 3 \times 9(M^{↑↑})$ mm$^3$ to reduce eddy current loss in the magnets.

The PM hysteresis loss calculation procedure develops further the principles introduced in [8]. The PM poles of the machine

| Parameter                      | Value            |
|--------------------------------|------------------|
| Air-gap length $\delta$ [m]    | $1.2 \times 10^{-3}$ |
| Electrical frequency $f$ [Hz]  | 1666.6           |
| Machine length in the axial direction $l$ [m] | 0.099 |
| Number of pole pairs $p$       | 10               |
| Number of series turns per phase per stator $N$ | 40          |
| Number of stator slots $Q_0$   | 24               |
| Period when magnetic field values at each magnet point are repeated $t_s$ [s] | $5 \times 10^{-4}$ |
| Permanent magnet height $h_{PM}$ [m] | 0.009 |
| Permanent magnet width $w_{PM}$ [m] | 0.04 |
| Permanent magnet length in axial direction $l_{PM}$ [m] | 0.099 |
| Rated speed $n_{rated}$ [rpm]  | 10000            |
| Ratio of slot opening to tooth tip width $b_t$ | 0.46  |
| Rotor external radius $r_e$ [m] | $158 \times 10^{-3}$ |
| Rotor internal radius $r_i$ [m] | $135 \times 10^{-3}$ |
| Stator external radius $r_w$ [m] | $133.8 \times 10^{-3}$ |
The magnetic field strength variation in each PM volume is calculated with 2D FLUX™ by Altair for time $t_v$:

$$ t_v = \frac{1}{f} \cdot \frac{2p}{Q_s} \tag{11} $$

where $p$ is the number of pole pairs, $f$ is the electrical frequency, and $Q_s$ is the number of the stator slots. The time period $t_v$ determines the smallest time when every elemental volume of the machine’s magnetic pole is exposed to all possible values of the magnetic field strength during a specific operation mode. The FE-calculated magnetic field strength values are used as the input data for the introduced modeling approach. The hysteresis loss in the PMs of the machine designs studied are calculated as the sum of the losses in the PM volume created by the “hard” magnetic phases $E_{\text{hyst,hard}}$ and the losses at the surface of PM created by the “soft” magnetic phases $E_{\text{hyst,soft}}$.

$$ E_{\text{hyst,hard}} = \frac{2 \cdot p \cdot V_{\text{hard}}}{(1 - V_2) \cdot k_1 \cdot k_2 \cdot t_v} \left( \sum_{i=1}^{k_1} \sum_{j=1}^{k_2} E_{\text{hard},i,j} \right) \tag{12} $$

$$ V_{\text{hard}} = h_{PM} l_{PM} w_{PM} - (h_{PM} l_{PM} + l_{PM} w_{PM}) + h_{PM} w_1 l_{PM} + w_2 h_{PM} w_{PM}) \cdot 2 \cdot h_{\text{layer}} \tag{13} $$

$$ E_{\text{hyst,soft}} = \frac{2 \cdot p \cdot h_{\text{layer}}}{t_v \cdot V_2} \left( \frac{h_{PM} l_{PM}}{k_1} \sum_{i=1}^{k_1} \sum_{j=1}^{k_2} E_{\text{soft},i,j} \right) $$

$$ + \frac{w_{PM} h_{PM}}{k_2} \sum_{i=1,k_1}^{k_2} \sum_{j=1}^{k_2} E_{\text{soft,i,j}} + \frac{2 \cdot w_{PM} h_{PM}}{k_1 k_2} \sum_{i=1}^{k_1} \sum_{j=1}^{k_2} E_{\text{soft},i,j} $$

$$ + \frac{2 \cdot h_{PM} \cdot l_{PM}}{k_1} \sum_{i=1}^{k_1} \sum_{j=1}^{k_2} E_{\text{soft,i,j}} \left( \frac{p_2}{p_1} \right) $$

$$ + \frac{2 \cdot w_2 \cdot w_{PM} h_{PM}}{k_1 k_2} \sum_{i=1}^{k_1} \sum_{j=1}^{k_2} E_{\text{soft},i,j} \right) \tag{14} $$

Fig. 9 depicts the calculated loss distribution in the PM region and FE-calculated maximum/minimum values of magnetic field strength for an electrical machine design with 793a PM grade at the nominal load as an example. The calculated eddy current loss and hysteresis loss in the PM material with respect to the load are presented in Fig. 10.

**IV. DISCUSSION**

The spatial distribution of the volumetric hysteresis loss in Fig. 9(a) is typical for the chosen design topology [7], [8].
The spatial location of the surface-located hysteresis loss along the machine’s radial direction is depicted in Fig. 9(b). It follows the same trend as in Fig. 9(a), which is dictated by the time and spatial distribution of the magnetic field strength in PM domain during the machine’s operation. However, the narrow region in Fig. 9(b) along the machine’s radial direction generates a comparable value of hysteresis loss as in the regions close to the airgap. The data in Table II and in Fig. 9(c) show that the magnetic field strength variation in some PM parts deeper in the magnet is in the suitable range to cause significant demagnetization and magnetization of phase 2.

The model-simulated data in Fig. 9(a) and (b) shows that the hysteresis loss generated by the “soft” magnetic phase on the surface of the PM is several orders of magnitude higher than the hysteresis loss in the volume of the PM in the “hard” magnetic phases. This corresponds to the results available in the literature [3], [4], [10], [11], [22]. Nevertheless, the shares of the surface- and volume-located hysteresis loss in Fig. 10 are different in the studied PMSMs, although they have similar geometrical dimensions.

The slotting effect and the tooth tip leakage flux have a higher effect on the total magnetic field variation inside the PMs compared with the armature reaction effect in the design with 512a grade as the relatively low coercivity of this grade restricts the armature current to around 25% in comparison to the PM motor with 793a PM grade. Figs. 3 and 6(c), and the data in Table I show the volume-located magnetic phase 3 has a higher polarization value in comparison to the surface-located regions formed by the phase 2.

The “hard” magnetic phase can form hysteresis loops with considerable amount of energy already in the second quadrant of the intrinsic JH-plane. In PMSM with 512a magnets the volume-located hysteresis loss is dominant, Fig. 10(a). In Fig. 10(b), the PM-surface hysteresis loss is larger than the volume-located hysteresis loss up to 1.2 × the nominal load in the PMSM design with the 793a grade. The armature reaction field is strong enough to cause the formation of considerable recoil loops by the “soft” magnetic phase (Figs. 7 and 9). The hysteresis loss created by the “soft” magnetic phase increases relatively fast in the load range 0.1–0.4 pu. A notable amount of the regions on the surface of the PM are prone to partial demagnetization at relatively low values of armature current. The hysteresis loss in the volume of the PM increase with the load of the machine and exceeds the surface-located hysteresis loss at around 1.2 pu load. The data in Fig. 10 demonstrate that the hysteresis losses are around 20% and 10% of the eddy current losses in 512a grade and 793a grade magnets, respectively.

V. CONCLUSION

Structural imperfections in real RE PMs can generate a significant hysteresis loss under the operating conditions in an electrical machine. The PM hysteresis loss may originate either from the volume- or surface-located magnetic phases with reduced coercivity. The PM segmentation was an effective means to reduce the eddy current loss in PMs. However, it created a layer of damaged grains on PM surfaces, which may increase the hysteresis loss in the material. This article was limited to a single machine topology having a very high specific power and was therefore more vulnerable to armature reaction caused problems in the PMs than average PM motors.

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