Dmitry Egorov

FERRITE PERMANENT MAGNET HYSTERESIS LOSS IN ROTATING ELECTRICAL MACHINERY
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Abstract

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Electrical machines with permanent magnets (PMs) find numerous applications in present energy-efficient technologies. A reasonable compromise in terms of costs and efficiency makes electrical machines with ferrite PMs a viable alternative to the widely used induction motors in some cases.

The loss analysis requires knowledge of all possible loss sources in an electrical machine. The hysteresis loss in the PM magnetic poles of a PM motor is usually excluded from the conventional loss analysis in the electrical machine design. However, there is some evidence that this loss may take place in the PM material under operating conditions relevant to electrical machinery.

In this doctoral dissertation, the focus of study is on the hysteresis behavior of ferrite PMs used in electrical machinery. Extensive measurements were performed by means of a Vibrating Sample Magnetometer (VSM) based system. The measurement procedure for the VSM was developed to be a relevant option in terms of electrical machine design. The detected magnetic phases with a reduced coercivity may introduce an additional loss source in the PM material when it is placed in a magnetic circuit of a PM electrical machine.

The hysteresis behavior of the ferrite magnets was simulated by the static History-Dependent Hysteresis Model (HDHM) with a newly introduced analytical equation for reversal curves. The HDHM concept was further developed to enable the simulation of ferrite magnets consisting of multiple magnetic phases with markedly different magnetic properties. The results of the study clearly indicate that the ferrite PM hysteresis loss does not play a significant role in most electrical machine designs. Nevertheless, the ferrite PM material can be a source of considerable hysteresis loss under unfortunate operating conditions in the region of the \( BH \) plane relevant to the electrical machine design.

Keywords: permanent magnet materials, hysteresis, modeling, losses, design of an electrical machine
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Dmitry Egorov
June 2019
Lappeenranta, Finland
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This doctoral dissertation is based on the following papers. The rights have been granted by the publishers to include the papers in the dissertation.


Author's contribution

Dmitry Egorov is the principal author and investigator in Publications I and III–V. In Publication II, Dr. Ilya Petrov was the corresponding author and Dmitry Egorov conducted the studies on the basic idea of the measurement procedure and the postprocessing of the measurement data.
Nomenclature

Latin alphabet

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>B</td>
<td>magnetic flux density</td>
<td>T</td>
</tr>
<tr>
<td>B_r</td>
<td>permanent magnet remanence</td>
<td>T</td>
</tr>
<tr>
<td>BH_max</td>
<td>maximum energy product</td>
<td>J/m³</td>
</tr>
<tr>
<td>H</td>
<td>magnetic field strength</td>
<td>A/m</td>
</tr>
<tr>
<td>H_a</td>
<td>applied magnetic field strength</td>
<td>A/m</td>
</tr>
<tr>
<td>H_d</td>
<td>demagnetizing field</td>
<td>A/m</td>
</tr>
<tr>
<td>H_i</td>
<td>intrinsic magnetic field strength</td>
<td>A/m</td>
</tr>
<tr>
<td>H_c</td>
<td>normal coercivity</td>
<td>A/m</td>
</tr>
<tr>
<td>H_cJ</td>
<td>intrinsic coercivity</td>
<td>A/m</td>
</tr>
<tr>
<td>H_max</td>
<td>maximum value of the magnetic field strength in the magnet when the magnetic field varies between $H_{min}$ and $H_{max}$</td>
<td>A/m</td>
</tr>
<tr>
<td>H_min</td>
<td>minimum value of the magnetic field strength in the magnet when the magnetic field varies between $H_{min}$ and $H_{max}$</td>
<td>A/m</td>
</tr>
<tr>
<td>ΔH</td>
<td>variation of the external magnetic field strength</td>
<td>A/m</td>
</tr>
<tr>
<td>J</td>
<td>magnetic polarization</td>
<td>T</td>
</tr>
<tr>
<td>N_m</td>
<td>magnetometric demagnetizing factor</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>surface area</td>
<td>m²</td>
</tr>
<tr>
<td>V</td>
<td>volume</td>
<td>m³</td>
</tr>
<tr>
<td>$\mu_r$</td>
<td>relative permeability</td>
<td></td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>permeability of vacuum, $4\pi \times 10^{-7}$</td>
<td>H/m</td>
</tr>
<tr>
<td>$\rho$</td>
<td>electrical resistivity</td>
<td>Ωm</td>
</tr>
</tbody>
</table>

Abbreviations

2D       | two-dimensional                                   |
AC       | alternating current                               |
DC       | direct current                                    |
FEA      | finite element analysis                           |
HDHM     | history-dependent hysteresis model                |
LRC      | linear recoil curve                               |
MEC      | magnetic equivalent circuit                       |
NMRSD    | normalized root mean square deviation             |
PM       | permanent magnet                                  |
PMSM     | permanent magnet synchronous machine              |
RSM      | rotor surface magnet                              |
RE       | rare earth                                        |
TCW      | tooth coil winding                                |
VSM      | vibrating sample magnetometer                     |
1 Introduction

The global trend in improvement in the energy-efficiency technology directly affects the development of electrical machinery. At the moment, electrical machines consume around 45% of the total generated electrical energy [1], being thus an object of significant research interest in terms of efficiency improvement. The progress in the permanent magnet (PM) technology has boosted the development of PM-based electrical machine designs. The high maximum energy product $BH_{\text{max}}$ in rare-earth (RE) based PM materials enables electrical machine designs with a higher power or torque density compared with other electrical machine alternatives operating at a similar power and speed but without permanent magnet material [2].

The penetration of electrical machine designs with RE PMs into the market is significantly constrained by the high price of the RE-based magnet materials. After the considerable price rise in 2011–2013, the cost of the raw RE materials for RE PM production (i.e., Samarium, Dysprosium, Neodymium) remains at a relatively high level or even demonstrates an increasing price trend [3]–[5]. An additional difficulty associated with the use of RE PMs in electrical machinery is caused by their unsustainable production process, price volatility, and possible threats of the supply chain of the RE raw materials [6]–[8]. The challenges related to the mass production of electrical motors based on RE PMs has boosted the research aiming to find alternative hard magnetic materials, which can be used in electrical machine design keeping the cost of the electrical machine at an acceptable level. Ferrite PM materials enable viable electrical machine designs in some applications where the machine volume has no strict limitations [9]. The price of the ferrite PMs remains significantly lower in comparison with RE-based magnets because of the relatively high abundance of raw materials needed for the ferrite PM production [10]–[12]. The relatively low $BH_{\text{max}}$ and intrinsic coercivity $H_{cJ}$ of ferrite PMs require thoughtful designs to achieve a competitive performance in comparison with other possible electrical machine designs [13]. The latest literature review clearly indicates that ferrite PM electrical machines can be an attractive option in some applications, such as electric propulsion systems [6], [14], hybrid electric vehicles [13], [15], high-speed motors [16], [17], submersible water pumps [18], wind power generators [19], [20], and others [21]–[24].

A detailed efficiency analysis requires evaluation of all possible loss sources in the magnetic and mechanical parts of an electrical machine. In traditional distributed winding machines applying RE PMs, the losses in PMs were initially not considered as they hardly contribute to the overall efficiency of the electrical machine [2]. However, the relatively low electrical resistivity $\rho$ of RE-based PMs within one to two hundred $\mu\Omega\text{cm}$ [12], [25] brought the PM loss into consideration in the context of eddy current loss theory. In particular, Rotor Surface Magnet (RSM) and Tooth Coil Winding (TCW) Permanent Magnet Synchronous Machine (PMSM) designs are in the scope of the research, as they enhance the presence of flux density harmonics penetrating through the magnets [26]–[29]. Nowadays, both analytical and finite-element-based approaches are available for calculation of eddy current losses in PMs [30]–[34]. Most of the commercial tools for
electrical machine design include eddy-current-theory-based calculation of losses in PMs [22], [35]–[39].

The electrical resistivity of ferrite PMs is around $10^{10} \mu \text{cm} (100 \Omega \text{m})$ [11]. Such a high electrical resistivity has established a common engineering practice to neglect any eddy current losses in this type of a hard magnetic material in rotating electrical machinery [9], [13], [40], [41].

Hysteresis loss generated by an alternating magnetic field in the electrical steel of the magnetic circuit of a machine is a well-known source of losses, and has been included in the efficiency analysis of machines for decades [2], [42]–[45]. The conventional representation of the PM as a material consisting of only one hard magnetic phase leaves, in principle, almost no space for a similar loss type within the normal operating range of an electrical machine. Nevertheless, the relative permeability $\mu_r$ slightly higher than unity implies a possibility of some hysteresis behavior in PMs [46]. Deviation from the permeability of vacuum indicates that there are some soft magnetic phases in permanent magnet materials.

Further, a magnet may include regions of magnetic phases with considerably weaker magnetic properties in comparison with the expected hard magnetic phase [47]–[51]. These regions can be located either in the PM volume or on the surface of the magnet [47], [48], [52]. The volumetric defects can originate from formation of some magnetic phases and local imperfections in the production of the PM [47], [48], [53]. The grains with a reduced coercivity on the surface are mostly an adverse effect of the machining production step [12], [52], [54].

A schematic comparison of the ideal and real hysteresis behavior of PMs is provided in Fig. 1. The main $JH$ curve of an ideal magnet (dashed line) has $\mu_r = 1$ and remains in parallel with the $H$-axis within the 1st and the 2nd quadrants of the intrinsic $JH$ plane up to the normal coercivity of the main hard magnetic phase $H_{c1}$. This region of an initially fully polarized magnet is called linear region. If the external demagnetizing field exceeds $H_{c1}$, the PM loses its polarization irreversibly. The value of $\mu_r$ for a typical PM is slightly higher than unity. This indicates at least a possibility of some hysteresis behavior of the main hard magnetic phase and results in some angle between the $H$-axis and the part of the PM main $JH$ curve within the linear region. The magnetic phases with smaller coercivities ($H_{c2}$ and $H_{c3}$) compared with the expected main magnetic phase may be present on the surface and in the inner volume of the magnet. The resulting main $JH$ curve of the PM within the linear region (solid black line) may have a considerable polarization decrease near the $J$-axis. The magnetic phases with reduced coercivities are able to form hysteresis loops in the linear region of the $JH$ plane of the magnet under variation in the external magnetic field strength. The hysteresis loop (hatched region) may include a considerable amount of energy if the variation in the external magnetic field strength $\Delta H$ is able to modulate the PM operating point from the 2nd to the 1st quadrant and back.
Regions with a reduced coercivity are able to form hysteresis loops under time-periodic variation in the magnetic flux in the PMs used in an electrical machine under unfortunate operating conditions [46]. Fluctuation in the flux density of the magnets in a synchronous electrical machine during operation is caused by space harmonics that are not in synchronism with the fundamental of the armature reaction field. These harmonics originate mostly from the spatial distribution of the armature reaction field caused by the current fundamental [13], [35], slotting effect [55], [56], tooth tip flux leakage, and local tooth saturation [57], [58]. The resulting magnetic field variation in the PM can magnetize and demagnetize the magnet regions with a reduced coercivity and thereby modulate the time periodic hysteresis loops that contain a considerable amount of energy. The hysteresis loss produced by the main magnetic phase and the regions with considerably weaker magnetic properties of the magnet are usually excluded from the conventional loss analysis of PM electrical machines.

1.1 Previous work

Several studies have been completed before this work on the hysteresis loss phenomenon in the PM magnetic poles of electrical machines. The study in [59] used a magnetically shorted system to measure losses in the neodymium iron boron (NdFeB) PM. The hysteresis loss and eddy current loss were estimated from the total measured loss by a two-frequency method. The determined hysteresis loss was converted into a function of electrical frequency and maximum flux density. Then, this hysteresis loss dependence was applied in the postprocessing of the Finite Element Analysis (FEA), where the flux variation in the PMs was estimated in an actual machine. The calculated hysteresis loss exceeded the eddy current loss by about 100% when the machine was running at the 50 Hz frequency.
The procedure applied in [59] is somewhat questionable from an electrical machine designer’s point of view. The magnetically closed measurement circuit of the PM alone is not a valid condition for a permanent magnet material in PM electrical machines as they have an air gap in their magnetic circuit. In addition, there is often a negative armature reaction present that opposes the magnetization of the PM and further demagnetizes the magnets. The air gap is seen as a considerable demagnetizing field acting on the magnet, and thus, the operating point of a magnet shifts to the second quadrant of the $BH$ plane. The possible time-periodic modulation of the magnetic field in the PM becomes nonsymmetric with respect to the $B$ axis of the $BH$ plane. Moreover, the hysteresis phenomenon implies a history-dependent magnetic behavior of a material, that is, the area of the recoil loop is significantly affected by the previous magnetic states of the system. Therefore, the hysteresis loss in every part of the PM pole cannot only be characterized by the maximum flux density that was obtained in a closed magnetic circuit.

The study of [54] used a closed circuit and measurement procedure like the ones used in [59] to estimate the total loss in two NdFeB PM grades. A considerable proportion of the measured loss cannot be explained by the classical eddy current loss theory. The permagraph (Magnet-Physik C-300) with a closed magnetic circuit measured the hysteresis behavior of two bulk samples. The considerable polarization decrease near the $J$-axis clearly demonstrates the presence of different magnetic phases with significantly different magnetic properties. The phases with a smaller coercivity are associated with the damaged grains on the surfaces of the samples. This claim is supported by the Kerr microscopy surface images (Evico magnetics GmbH) for both samples in the remanent state of initially fully polarized PM samples. The measurements were provided after the application of a DC demagnetizing field with a magnitude that is far from the nominal intrinsic coercive force $H_{cJ}$ of the studied grades; in other words, the magnets were not exposed to any notable irreversible demagnetization. The images, however, clearly indicate the partial irreversible demagnetization of the surface grains, thereby supporting the idea of the surface origin of the hysteresis loss in NdFeB magnets. The important results in [54] are the measured total loss under simultaneously applied sinusoidal alternating current (AC) and demagnetizing direct current (DC) magnetic fields. The applied DC field was used to simulate the operating conditions similar to those in the actual machine, which had an air gap and demagnetizing armature reaction. The measured loss under the simultaneously applied demagnetizing DC field and the AC field show a small difference compared with the eddy-current-loss-theory-calculated loss. The obtained result clearly indicates the minor contribution of the hysteresis loss to the total PM loss if the operating point of the magnet remains in the second quadrant of the intrinsic $BH$ plane of the magnet. Nevertheless, the measured data in [54] only demonstrate the common trend for hysteresis loss in a PM material. Exact calculation of the hysteresis loss in PMs of actual electrical machines was not provided.

The magnetic properties of small sintered NdFeB magnets were studied in [52]. The surface-to-volume ratio $S/V$ of the samples was varied within $5–36 \text{ mm}^{-1}$. It was reported that the magnetic phases with a reduced coercivity were located on the surface of the sample. The thickness of the damaged layer was estimated in the range of the mean grain
size. Coating with powders and further heat treatment of samples at temperatures higher than the melting point of the Nd-rich phase resulted in a considerable reduction in the magnetic phases with a reduced coercivity. The total hysteresis behavior of the treated bulk sample still included a notable contribution of the magnetic phases with a smaller coercivity, in other words, it was shown that no PM sample consists of a uniform magnetic phase.

The parameter $S/V$ can be useful to estimate the approximate volume of the surface-located regions with a reduced coercivity. The typical grain size for sintered RE PMs is reported to be in the range of 5–15 µm [52]. Assuming that only one surface layer is affected by the cutting procedure, the approximate volumetric proportions of the regions with a reduced coercivity in the studied samples in [52] were within 2.5–7.5% and 18–54% for the samples with $S/V = 5 \text{ mm}^{-1}$ and $S/V = 36 \text{ mm}^{-1}$, respectively. The larger PMs have a smaller $S/V$ ratio. The results indicate that RE-based PM machine designs with thin magnets may have a notable proportion of magnetic phases with a reduced coercivity. In addition, the segmentation of RE PMs is a conventional way to reduce the possible eddy-current-based loss in RE-based materials [35], [60]–[64]. Thus, the segmented magnetic pole of an electrical machine may have a higher hysteresis loss as a result of the cutting procedure, which produces a layer of damaged grains on the surface of PMs.

The behavior of the magnetic phases was studied in [53] for two NdFeB samples with markedly different magnetic properties. The hysteresis behavior measured by the Vibrating Sample Magnetometer (VSM) revealed two types of magnetic phases with a reduced coercivity. The first type of magnetic phase originates from the surface defects of bulk samples as similar magnetic phases are absent in the x-ray diffraction images (by BL01C2 of the National Synchrotron Radiation Research Center, Taiwan) of the powders that were used for the preparation of the bulk samples. The second type of magnetic phase may have a coercivity in the range of 0.03–0.4 of the expected coercivity of the bulk sample. The magnetic phases of the second type may originate from $\alpha$-Fe and FeB phases occurring in the production process or may even be associated with the Nd-rich phase at the grain boundaries. The Nd-rich phase is intentionally formed at the grain boundaries to enhance the coercivity of the NdFeB PMs. Therefore, part of the magnetic phases with a lower coercivity may be located in the volume of the PM.

The study reported in [46] addresses hysteresis loss in NdFeB PMs under the operating conditions of electrical machines. The amount of hysteresis loss was not properly assessed owing to the limited measurement data available. Nevertheless, the study provides discussion about the PM electrical machine design topologies that may be prone to hysteresis loss in a PM material. Another contribution of [46] is the Permagraph measurements (C-300 by Magnet-Physik), which clearly demonstrate the inapplicability of this measurement tool for studies of the hysteresis behavior of RE-based PMs; eddy currents in the bulk PM material heavily corrupt the measurement output. The VSM measurement system (by Quantum design), however, showed a better ability to observe the magnetic behavior of hard magnetic materials with a low electrical resistivity, even though the measurement results were not treated appropriately.
At the time this doctoral dissertation started there was a clear contradiction between the existing engineering practice and studies published. A convenient design procedure of an electrical machine with PMs only included eddy-current-theory loss estimation in the PM material, whereas the studies available reported a notable contribution of hysteresis loss in the total loss of a magnet [46], [54], [59]. There was no established practice of VSM-based measurements of high coercivity PMs with correct postprocessing of results in terms of electrical machinery. Before this study, the hysteresis loss in PMs of electrical machines has not been assessed with a reasonable accuracy in real operating conditions of the PM material in rotating electrical machinery.

1.2 Outline of the doctoral dissertation

The objective of this doctoral dissertation is to evaluate the amount of hysteresis loss in a ferrite PM material during its operation in the magnetic circuit of a PM-excited rotating electrical machine.

The author of this doctoral dissertation is the principal author and investigator in Publications I and III–V, and is solely responsible for the scientific contributions of the papers and the introductory part of the dissertation. In Publication II, the author is responsible for the basic theoretical considerations of the measurement procedure and postprocessing of the measured data.

Publication I focuses on the factors affecting the hysteresis loss in a PM material when it is placed in the magnetic circuit of a rotating electrical machine. The magnetic field in the PM region is estimated by the 2D FEA tool and a slotless analytical modeling approach. A new equation is introduced for the radial component of the armature reaction field inside the magnetic pole of a machine. The nonsinusoidal spatial distribution of the armature current fundamental and the modulation of the field in the PM material by the slotting effect are found to be the major factors that cause the possible hysteresis loss in the TCW RSM PMSM configuration. The inverter current time harmonics, local tooth saturation, and tooth tip leakage flux are less significant phenomena. The publication complements the analytical slotless modeling approach, which offers a fast and relatively simple tool for the initial step of an electrical machine design.

Publication II studies the hysteresis loss in three distinct PM grades (Ferrite, SmCo, and NdFeB) relevant to the electrical machine design. It introduces a new methodology concept to estimate the amount of hysteresis loss in the PM magnetic pole of a PM electrical machine. The electrical machine design topologies prone to hysteresis loss are discussed. Finally, the approximate amount of hysteresis loss in the PM material of two essentially different electrical machine designs is calculated by combining the magnetic flux density values in the PM region estimated by the 2D FEA and the hysteresis behavior of the magnets measured by the VSM. The efforts to reduce the hysteresis loss in some cases are discussed.
Publication III estimates the hysteresis loss in the ferrite PM material of the RSM TCW PMSM used in a hybrid electrical vehicle. A VSM-based measurement system is used to observe the hysteresis behavior of a sample that was cut from the PM pole of the machine. The methodology concept from Publication II is further developed to enable accurate estimation of the PM hysteresis behavior. A new equation is introduced for the history-dependent hysteresis model (HDHM) to enable accurate simulation of the ferrite PM material, and other possible modeling options are also discussed. The reptation (accommodation) phenomenon is demonstrated for the ferrite PM material. The VSM measurements do not demonstrate a significant presence of magnetic phases with a reduced coercivity in the studied sample. The calculated losses in the PM material are found to be negligible under the operating conditions of the observed electrical machine design both for pure sinusoidal and frequency converter supplies. The paper provides a useful insight into advanced modeling of a PM material in rotating electrical machinery. The results are in perfect agreement with the prevailing engineering practice, where the hysteresis loss in a hard magnetic material is neglected if the magnet operates in the linear part of the main $BH$ demagnetization curve.

Publication IV extends the studies of hysteresis loss for three distinct commercially available ferrite PM grades, which are stock materials from a Chinese manufacturer. The VSM measurements reveal a considerable presence of magnetic phases with a reduced coercivity for all three samples under study. The hysteresis loss estimation is based on the same methodology as in Publication III; however, a new modeling technique is introduced to simulate the hysteresis behavior of the ferrite PM in rotating electrical machinery when the bulk ferrite magnet manifests a simultaneous presence of magnetic phases with significantly different magnetic properties. The proposed modeling principle is successfully verified by a total of six independent measurements. The hysteresis loss is calculated for the RSM TCW PMSM topology used in Publication I, Publication II, and Publication III, and for the axial flux TCW PMSM design. The results clearly show a considerable contribution of the magnetic phases with a reduced coercivity to the total hysteresis loss in the PM material, even though these losses are small in practice. The calculated hysteresis loss map clearly indicates that the amount of hysteresis loss in the ferrite PM material can be considerable in unfortunate operating conditions.

Publication V addresses the linear-recoil-curve (LRC) modeling concept for the FEA simulation of ferrite PMs in rotating electrical machinery. The LRC-concept-based models in the present-day FEA software available for electrical machine design are discussed. A new procedure is introduced for VSM-based measurements of the PM hysteresis behavior in the 2nd and 3rd quadrants of the intrinsic $BH$ plane. The studies on the general accuracy of the LRC concept provide a useful insight into the possible FEA computation error, which may result from an inappropriate choice of the model.

Chapter 1: The research topic and its practical importance are addressed in brief. Previous studies are analyzed.

Chapter 2: The main findings and contributions of Publications I–V are presented in short.
Chapter 3: Conclusions are discussed and suggestions for future work are provided.

1.3 Scientific contribution

This doctoral dissertation investigates the amount of hysteresis loss in ferrite PM materials used in rotating electrical machinery. The scientific contributions of the dissertation are summarized as:

- New analytical equation for the armature reaction field is introduced to the slotless modeling concept. The equation is able to estimate the radial magnetic flux density component both in the air gap and magnet region of the machine. The proposed equation simplifies the estimation of the magnetic field in the magnets of radial-flux electrical machines and makes the slotless modeling concept more appropriate for the study of the hysteresis loss phenomenon in magnets used in rotor-surface-magnet electrical machines. A similar equation for armature reaction field can be derived for axial flux PMSMs.

- Methodology for the VSM-based measurements of PM intrinsic magnetic properties is established. The VSM measurement system enables high-precision measurements of magnets with a high coercivity.

- The HDHM concept is developed further to enable the simulation of the hysteresis behavior of ferrite magnets. The proposed new equation for the reversal curves is able to simulate with fair accuracy the ferrite PM material consisting of one magnetic phase.

- A new concept is introduced to simulate the hysteresis behavior of ferrite PMs in the region relevant to electrical machine design. The concept is able to simulate the hysteresis response of the ferrite PM sample, which consists of multiple magnetic phases with markedly different magnetic properties.

- The hysteresis losses are estimated in four distinct ferrite PM grades in conditions relevant to the actual use of the material in rotating electrical machinery.

- The proposed VSM-based measurement methodology enables detailed, accurate studies of the LRC concept for the simulation of PMs in rotating electrical machinery. The results clearly show that the LRC principle offers a simple and powerful tool for FEA simulation in rotating electrical machinery, which, however, can be a source of considerable error in some cases.
2 Publications

This chapter provides an overview of the three journal and two conference papers.

2.1 Publication I

The phenomena affecting the hysteresis loss in the PM material of a PM electrical machine are discussed in Publication I. A 50 kW ferrite PM synchronous machine with an external rotor topology, rotor-surface-magnets, and tooth coil winding configuration [65] is used as the study case. A sketch of the machine is depicted in Fig. 2. The parameters and dimensions of the observed RSM TCW PMSM are provided in Publication I. The chosen electrical machine design can be exposed to large PM hysteresis loss because of the rotor-surface-mounted magnets, a high amount of permeance harmonics caused by the current linkage spatial distribution, and relatively large slot openings. The slotless analytical model [66]–[70] is refined for the task. The slotless approach is a reasonable compromise in terms of accuracy, implementation complexity, and calculation time compared with other possible analytical options, such as the magnetic equivalent circuit (MEC) method [71]–[75] and subdomain models [76]–[78]. The field of a single coil is derived by a solution of the Laplacian equation in the air-gap region. A new formulation for the armature reaction field for the slotless modeling concept is presented. The derived analytical equation only needs the main parameters of the winding and the time-dependent values of the phase currents. On the contrary, the original expression of the armature reaction field [67] requires a spectrum analysis of the phase current and winding-specific harmonics.

![Figure 2: 2D sketch of the RSM TCW PMSM with the external rotor used in the study.](image_url)

The analysis of the field distributions in the magnet region reveals that the nonsinusoidal armature reaction spatial field distribution of the stator current linkage and the slotting effect have the highest effect on the modulation of the PM operating point in the normal
operating mode. The tooth saturation phenomenon cannot be taken into account by using an analytical approach owing to the assumption of the constant relative permeability $\mu_r$ of steel. This contributes to the total error between the analytical and FEA calculation of the magnetic field in the PM region. The results calculated by the FEA show that tooth saturation may cause an additional fluctuation of the PM operating point and thereby increase the total hysteresis loss. The influence of the inverter-caused current harmonics on the modulation of the PM operating point is found to be negligible.

The slotless modeling concept applies an idealized geometry of the slot, which neglects the tooth tip flux leakage. This contributes to a difference between the FEA and the analytical results. Nevertheless, an analytical approach can be accurate enough to evaluate the possibility of hysteresis loss in PMs in the initial design stage of an electrical machine. The presented analytical solution of the armature reaction field can be extended to other winding configurations for electrical machines with internal, external, or axial-flux rotor topologies.

A comparison of the magnetic flux density distributions calculated by the FEA and simulated by the model is depicted in Fig. 3 at the surface of the magnetic pole close to the air-gap region. The modulation of the flux density by the discussed phenomena is highest at the surface of the magnetic pole close to the air gap, and it is mitigated considerably inside the magnet. Further details can be found in Publication I.

Figure 3: Magnetic flux density on the surface of the magnetic pole of the machine close to the air gap: (a) FEA results, (b) model results. 1 – effect of slot opening, 2 – tooth saturation effect, 3 – effect of tooth tip leakage flux, and 4 – effect of the current time harmonics caused by the non sinusoidal converter supply. The analytical approach neglects the effects of the tooth tip leakage flux and the local tooth saturation. The studied electrical machine has ferrite PMs (BM9 grade) with the remanence $B_r = 0.34$ T and the relative permeability $\mu_r = 1.26$. The value of $\mu_r$ used in the FEA model is not supported by the experimental data from Publication III, where $\mu_r \approx 1.04$ is calculated for a ferrite PM sample of BM9 grade at 83°C. This does not affect the conclusions in Publication I.
2.2 Publication II

Three distinct PMs (NdFeB, SmCo and Ferrite) are studied for the possible hysteresis loss in Publication II. The test installation consists of a Physical-Properties-Measurement System with up to 14 Tesla superconducting magnets by Quantum Design with a P525 VSM option and a data collection system. The sensitivity of the measurement system enables the detection of magnetization changes less than $10^{-6}$ emu at the data rate of 1 Hz. The measurement temperature can be set in the range of 1.9–350 K. The AC frequency range and the AC amplitude range are 10–10000 Hz and $2 \times 10^{-3}$–15 Oe, respectively [79]. The magnetic field variation is programmed in compliance with the required measurement sequence. VSM measurements clearly indicate the contribution of different magnetic phases with a reduced coercivity to the total magnetic behavior of the samples when the operating region of the magnet along its $BH$ plane is relevant to the electrical machine design. The amount of hysteresis loss in two essentially different machine designs is approximately estimated by several measured hysteresis loops, and the magnetic field distribution in the magnet region of the electrical machines is calculated by the 2D FEA. The first machine design is represented by an RSM TCW permanent magnet synchronous machine (PMSM) with an external rotor topology [65]. The PM pole in such a design can be exposed to a significant variation in the magnetic field. The variation in the magnetic field is mostly caused by the highly nonsinusoidal armature reaction field of the stator current linkage distribution and the slotting effect, as discussed in Publication I. The second machine design is a PM motor with a low number of poles. In such a design, the combination of the armature reaction field and the slotting effect can produce considerable magnetic field strength variation in some regions of the magnet. The calculated hysteresis loss in the PM poles of the studied electrical machine designs is estimated to be up to 1.4% and 1.1% of the nominal efficiency of the motor for the RSM TCW PMSM and the low pole number PMSM, respectively.

The publication includes some misunderstandings, which are further explained in Publications III–V. In the study, the measurement temperature was set to 23°C, which generally does not correspond to the actual thermal operating range of a PM material in rotating electrical machinery. The magnetic properties of the PMs are significantly affected by the temperature. The operating temperature in an electrical machine can be notably higher as a result of the losses generated in other parts of the machine and the cooling method. The measurement temperature was set to 80–83°C in Publications III–V, which is a reasonable thermal design consideration for some type of PMSM [2], [65], [80].

The open magnetic circuit measurement system of the VSM provides numerous advantages over other options available (i.e., hysteresisgraph, pulsed field magnetometer, permagraph) [81], [82] when very accurate measurements of high coercivity materials are needed. The system provides an opportunity of long-time measurements with a predefined temperature in high magnetic fields. The low speed of the field change mitigates eddy currents in the bulk material of the sample. The measurement data are not distorted by eddy currents and hysteresis in the magnetic yoke of the measurement system.
The adverse effect of the open magnetic circuit measurement system is the high demagnetizing field acting on the sample. Fig. 4 shows the field inside the magnet when it is placed in an open and closed magnetic circuit. The VSM results represent polarization versus applied field, where the applied field has to be corrected to the intrinsic field of the sample by the demagnetizing field. The inappropriate correction of the measured results by the demagnetizing field in this publication results in an overestimated total hysteresis loss because the measured recoil loops are shifted to the second quadrant of the BH plane. The resulting hysteresis loss in the magnetic poles of the machine design under study is calculated based on the maximum values of the magnetic flux density during the slot period, which leads to neglecting the additional field flux density variation caused by the tooth saturation phenomenon. The measurement procedure and the loss calculation technique are further developed in Publications III–V.

Figure 4: Field inside a magnet. a) Closed magnetic circuit. The applied magnetic field strength $H_a$ is in the direction of the polarization $J$. There is no demagnetizing field $H_d$ occurring in the magnetic circuit without an air gap. The intrinsic magnetic field strength inside the magnet $H_i$ is the same as the applied field strength $H_a$. b) Magnetic circuit with an air gap, no external field is applied. A demagnetizing field $H_d$ occurs in the magnet, which is placed in the magnetic circuit with an air gap. A demagnetizing field is directed opposite to $J$ and always tries to demagnetize the magnet. The field inside the magnet $H_i$ is the same as the demagnetizing field $H_d$. c) Magnetic circuit with an air gap and $H_a$ applied against the polarization direction. The field inside the magnet is the vector sum of $H_i$ and $H_d$.

2.3 Publication III

In Publication III, the hysteresis loss is assessed in the magnetic poles of the RSM PMSM with an external rotor topology and a TCW configuration [65]. The machine design topology is the same as in Publication I and Publication II. The hysteresis behavior of the studied sample is measured by the VSM at the temperature of 83°C. The VSM results are appropriately corrected by an analytically calculated magnetometric demagnetizing factor [83]. The hysteresis behavior of the studied sample is simulated by the History-Dependent
Hysteresis Model (HDHM) concept [84] with a newly introduced equation for the hysteresis behavior of reversal curves.

The HDHM concept is not the only option to simulate the problem under study. There are numerous hysteresis models available; another possible solution can apply for instance Preisach-type models [80], [85], general Positive-Feedback theory [86], [87], Magneto-Static Modeling Approach [88], Stop and Play models [89], [90], and others [87], [91]. The choice of the HDHM concept is based on its implementation simplicity and flexibility compared with other options. A detailed literature review of suitable hysteresis modeling approaches is provided in this publication.

The reptation (accommodation) phenomenon may affect the choice of the analytical approach used to simulate the hysteresis behavior of the material. Many hysteresis-modeling concepts available include implicitly or explicitly the return point memory of reversal curves [22], [31], [36], [37], [50], [80], [82], [85]–[87], [89]–[92]. A detailed discussion can be found in this publication. The reptation (accommodation) phenomenon in ferrite magnets is demonstrated by measurements and discussed.

The measured data do not demonstrate hysteresis behavior similar to that reported in Publication II for the ferrite PM sample of the same BM9 grade. Instead, the hysteresis behavior of the sample correspond to a magnet consisting primarily of a uniform hard magnetic phase. The measured and calculated hysteresis loops are in good agreement. Fig. 5 depicts a comparison of the measured and the model-simulated reversal curves near the $J$-axis of the initially fully polarized PM. The total hysteresis loss in the magnetic poles of the studied electrical machine design is estimated by applying a

![Figure 5: Comparison of the measured (solid lines) and model-simulated (circles) hysteresis behavior of the PM (BM9 grade) at 83°C. The main $JH$ curve of the initially fully polarized PM (solid-dot line) does not demonstrate a significant polarization decrease near the $J$-axis.](image-url)
combination of the commercial FEA tool Flux by Altair/CEDRAT and the HDHM analytical approach with the proposed equation for the reversal curves. The magnetic field variation in each elemental volume of the magnetic pole of the machine calculated by the 2D FEA is used as the input data for the HDHM. The hysteresis loss is determined to be 0.0082% and 0.0084% of the machine nominal power for pure sinusoidal and frequency converter supplies, respectively. The results clearly indicate the relevance of the prevailing engineering practice to assess the loss in ferrite PMs if no magnetic phases with a reduced coercivity are present in the volume and at the surface of the ferrite PM material.

2.4 Publication IV

The data measured by the VSM for the two distinct ferrite PMs from the same batch exhibit markedly different hysteresis behavior of the recoil curves, as it can be seen in Publications II and III. The PM sample in Publication II displays a knee in the hysteresis loops in low demagnetizing fields while the sample in Publication III shows an expected hysteresis behavior of the bulk magnet with a homogeneous hard magnetic phase. In this publication, the hysteresis behavior of three distinct commercially available ferrite PM grades is studied. The batches are from a Chinese manufacturer. According to the producer, the magnets were produced by a hydrothermal synthesis method. The VSM measurement data show a considerable polarization decrease near the $J$-axis for all the samples under study, which indicates the presence of magnetic phases with a reduced coercivity in the bulk sample material.

Studies available on the topic report on possible formation of iron oxide $\alpha$-$\text{Fe}_2\text{O}_3$ [47] and barium oxide $\text{BaFe}_{12}\text{O}_{19}$ [48] as unwanted magnetic phases if the hydrothermal synthesis method is used in the production of ferrite magnets. The coercivities of the undesirable magnetic phases are considerably lower compared with the expected $\text{BaFe}_{12}\text{O}_{19}$ magnetic phase of the hexagonal M-type ferrite PM. The measurement results from other studies [49], [51], [93] indicate that the coercivities of the magnetic phases with weaker magnetic properties can be in the range of knees observed in the samples. A detailed literature review is provided in this publication. The common electrical machine design practice is to use thick ferrite magnets in the PMSM magnetic poles because of the relatively weak magnetic properties of this material compared with RE PMs. Therefore, it is assumed that the measured hysteresis behavior of the samples can be treated as a response of a bulk sample that has evenly distributed volume regions with considerably weaker magnetic properties.

The measured hysteresis behavior of the samples is caused by a simultaneous contribution of numerous different magnetic phases in the volume of the sample. Available hysteresis models are used to simulate the regions consisting of one magnetic phase, and cannot thus be applied to the problem under study without modification. The newly introduced procedure is used to reproduce the hysteresis behavior of the samples by a simultaneous contribution of ‘soft’ and ‘hard’ magnetic phases. According to the standard No. 0100-
from the Magnetic Materials Producer Association, a magnetically hard material has a coercivity higher than 120 Oersteds (9550 A/m) [94]; the ‘soft’ artificial magnetic phase is hard by nature, and it is called ‘soft’ just because of the presence of the magnetic phase with a considerably higher coercivity (which is referred to as a ‘hard’ magnetic phase). The introduced separation technique is not the only option available; the general requirement for the resulting main hysteresis loops is the absence of the nonphysical behavior, that is, $\Delta J/\Delta H > 0$ must be true always. The model parameter identification procedure is performed simultaneously for both the artificial ‘hard’ and ‘soft’ magnetic phases. The hysteresis behavior simulated by the model shows a very good agreement with the experimentally obtained data for all three samples under study (a total of nine distinct measurement sequences). Fig. 6 depicts the example comparison of the measured and model-simulated hysteresis behavior of the PMs close to the $J$-axis of the initially fully polarized magnets.

![Figure 6: Measured and model-simulated hysteresis behavior of the samples under study.](image)

The hysteresis loss in the magnetic poles of two different electrical machine designs are studied. The procedure is similar to the one used in Publication III. The values of the magnetic field strength calculated by the 2D FEA are used as the input data for the proposed hysteresis modeling approach. First, an electrical machine design with an
external rotor topology and a TCW configuration is investigated. The estimated hysteresis loss is significantly higher compared with the original design with the BM9 grade in Publication III; nevertheless, the proportion of the loss does not exceed 0.056% of the nominal power of the machine. The second design is a 100 kW 1500 rpm axial flux PMSM introduced in [35]. The original design of the motor with NdFeB magnets had around 15 kW of eddy current loss in the PM material. The eddy current loss is reduced by placing laminated iron stacks on top of the RE PMs, which are close to the air gap. Application of ferrite PMs does not require similar design efforts because of the high electrical resistivity [11]. The original design [35] is updated for the study case: 1) the iron laminated stack is removed, 2) the RE PMs are substituted by the ferrite PM grades under study, and 3) the armature reaction field is reduced to avoid irreversible demagnetization of the ferrite PMs. The analysis shows that the hysteresis loss in the magnetic pole of the machine is about 0.3% of the nominal power.

Another important contribution of this publication is the map of the energy stored in the hysteresis loops. Fig. 7 depicts the hysteresis loss map for the Y32H-2 grade at 80°C as an example. The calculated data demonstrate a small hysteresis loss if the operating point of PM is located in the second quadrant of the intrinsic $BH$ plane of the magnet, which is the usual region of PM operation is rotating electrical machinery. The result is in agreement with the studies for the NdFeB magnet in [54]. There, the results were obtained by a magnetically closed measurement system and a two-frequency method. The results in Publication IV and in [54] clearly show that hysteresis loss does not play a significant role if the operating point of the magnet does not cross the $B$ axis during the operation and remains in the region of the main $BH$ demagnetization curve in the 2nd quadrant of the $BH$ plane, where no irreversible demagnetization of the magnet is assumed. However, the contribution of the hysteresis loss in the total loss of a magnet can be notable if the magnetic field strength is able to modulate the PM operating point within the 2nd and the 1st quadrant of the intrinsic $BH$ plane of the magnet. The exact amount of hysteresis loss in the RE-based PM magnetic poles of an electrical machine has not been properly assessed, and thus remains to be studied in more detail in further studies.

2.5 Publication V

The PM material used in the magnetic circuit of an electrical machine can be irreversibly demagnetized under high negative magnetic field strengths [2]. The irreversible demagnetization of a PM magnetic pole can be a result of anomalous operating conditions [95]–[100] or an inappropriate cooling method [101]–[106]. The usual design procedure of the electrical machine with a PM material includes assessment of the PM irreversible demagnetization. At the present time, an electrical machine design procedure often relies on FEA software, where various implementations of the Linear Recoil Curve (LRC) modeling concept are mostly used. Examples include Flux by CEDRAT/Altair [37], ANSYS Maxwell [31], COMSOL Multiphysics [36], and JMAG [22]. The studies in [36], [50], [82], [92] assume that the LRC-based demagnetization models provide a fair assessment of irreversible PM demagnetization if model-simulated and measured main
Figure 7: Energy density [J/m³] stored in the hysteresis loop of the PM sample (Y32H-2 grade) studied when the internal magnetic field varies between \( H_{\text{min}} \) and \( H_{\text{max}} \). The magnet is initially fully polarized. The measurement temperature is 80°C. The percentage values show a comparison of the measured and model-simulated recoil loops where available. The difference is small in the relevant areas.

demagnetization curves are in good agreement. However, possible sources of inaccuracy of the LRC concept itself are usually out of consideration. At the same time, recent studies of partial PM demagnetization report a significant difference between measured and FEA-simulated PM partial demagnetization both for electrical machine design [50], [107], [108] and general studies of irreversible demagnetization of the magnet [36], [109], [110].

Publication V provides an insight into the possible FEA computation error that originates from the assumptions in the LRC concept itself. The proposed measurement algorithm enables VSM measurement of the minor loops within the 2nd and 3rd quadrant of the intrinsic magnet \( BH \) plane, which are the most interesting ones for an electrical machine designer. Fig. 8 demonstrates the principle of the proposed measurement procedure. Fig.
9 provides a comparison of the studied LRC-based models in terms of accuracy. The measured data of the Y28H-2 ferrite PM grade at 80°C are used in the case study. The Normalized Root Mean Square Deviation (NRMSD) is chosen as an adequate quantitative tool to compare the accuracy of the models [50], [91]. The comparison of the measured and simulated macroscopic hysteresis behavior for the Y28H-2 ferrite PM

Figure 8: Principle of the measurement procedure applied in the study. The intrinsic recoil loops A’–B’–A’ and C’–D’–C’ (dashed lines) in the 2nd and 3rd quadrants can be obtained from the respective VSM measured curves A–B–A and C–D–C (dash-dotted lines). The points B and D where the VSM field reverses are determined in real time with $H_a = N_m \times J / \mu_0$. The value of $N_m$ is calculated analytically assuming $\mu_r = 1$.

Figure 9: NRMSDs for the LRC-based demagnetization models under study (Y28H-2 grade at 80°C). The figure differs from the version in Publication V. The error in Publication V is corrected here.
grade indicates that a universal LRC-based formulation does not exist. The linear sloped
exponential and hyperbolic tangent function models show a comparable accuracy in the
linear region of the $BH$ curve of the magnet in the 2nd quadrant. The linear sloped and
exponential model have a better accuracy at the beginning of the knee region; however,
at lower negative field strengths the error of these models becomes unacceptable. The
hyperbolic tangent function model manifests less erroneous results in the demagnetizing
fields below the coercivity $H_c$ of the magnet and should be preferred in the
demagnetization analysis after severe faults.

The spline-based models have the best accuracy compared with the previously discussed
options, as the analytical and measured main demagnetization $BH$ curves match exactly.
Linear sloped, exponential and tangent function models can be easily made as
temperature-dependent models based on a small number of coefficients. The spline-based
formulation of the LRC approach requires more memory space because the data for the
$BH$ curve at each temperature should be tabulated.
3 Conclusions and future work

3.1 Conclusions

This doctoral dissertation investigated the hysteresis behavior of some commercially available PM grades for electrical machine design. The regions of phases with a reduced coercivity were found to be an additional source of losses in a PM material under the operating conditions of PM-excited electrical machines. The PMSM configurations with the TCW topology and the RSM PM rotor structure were of the highest interest. The PM materials in such designs were exposed to a considerable variation in permeance harmonics penetrating through the magnets. The estimated PM hysteresis loss in ferrite PM-excited PMSMs did not significantly contribute to the total loss of the machine. Nevertheless, PM hysteresis loss represented a source of additional loss in a PM material.

The hysteresis loss may lead to an elevated temperature of a PM magnetic pole, which may change its magnetic properties. The amount of hysteresis loss in a ferrite PM material may be high in unfortunate operating conditions, for instance, when the external field strength is able to modulate the magnetic state of the initially fully polarized magnet within the 2nd and the 1st quadrants of the BH plane with high enough positive values of the magnetic field strength. Such operating conditions are not the case for ferrite PM-excited PMSMs because of the presence of an air gap and the general design considerations to avoid partial irreversible demagnetization of PMs in the normal operating mode.

The results of the research contribute to the hysteresis modeling theory and the measurement methodology of hard magnetic materials. The introduced theory enables the HDHM concept to be used to simulate the hysteresis behavior of ferrite PMs consisting either of one uniform or numerous markedly different magnetic phases in the region relevant to electrical machine design. The modeling theory can be adopted to other hysteresis concepts that incorporate the return point memory property of reversal curves. The established VSM-based measurement methodology allows highly accurate measurements of high coercivity PM materials. The measurement data can be applied to the further development of PM simulation approaches in electrical machine design.

A practical problem related to this work and the usage of permanent magnet materials in the design of electrical machines is that the PM material to be used should be exactly measured a priori to model its hysteresis behavior. The difficulty can be seen when comparing the results of Publications II and III. In principle, the same material displayed different hysteresis behaviors in different measurement sessions. Obviously, the sample in Publication II had suffered from some kind of damage for instance when preparing the sample for the tests.

A general guideline to mitigate permanent magnet hysteresis losses in electrical machines is to design the machine so that its permanent magnets always operate in the second
quadrant of the $BH$ curve. Crossing the $B$-axis can be dangerous and cause significant hysteresis losses in PMs.

### 3.2 Suggestions for future work

The amount of hysteresis loss in RE PMs has not been assessed with a similar accuracy as it was done in the case of ferrite PMs. At the same time, the physical and geometrical properties of RE-based magnets used in electrical machine design may result in considerably higher hysteresis losses compared with those of ferrite PM materials. The introduced modeling theory can also be extended to RE PM materials, which will provide a relatively accurate analytical tool to estimate the amount of hysteresis loss in RE-based PM magnetic poles of PM electrical machines. LRC-based models are widely used for the simulation of RE-based PMs in electrical machinery. A study on the accuracy and limitations of the LRC modeling concept can also be provided for RE PM materials, which are relevant to the electrical machine design.
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Publication I

Egorov, D., Uzhegov, N., Petrov, I., and Pyrhönen, J.
Factors affecting hysteresis loss risk in rotor-surface-magnet PMSMs

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Factors Affecting Hysteresis Loss Risk in Rotor-Surface-Magnet PMSMs

D. Egorov, N. Uzhegov, I. Petrov and J. Pyrhönen

Abstract -- In early papers about Permanent Magnet Synchronous Machines (PMSMs) it was often stated that there are no rotor losses in PMSMs. Later, eddy current analyses for sintered permanent magnets (PMs) have been dominating the rotor loss analyses. However, in some designs also hysteresis losses can be possible in PMs. This paper uses 2D Finite Element Method (FEM) program and 2D slotless analytical model to show the main factors affecting the hysteresis loss emergence and the applicability limitations of the existing analytical approaches in evaluating the hysteresis loss. A Tooth Coil Winding PMSM prototype with external rotor topology is used in the analysis as a reference.

Index Terms--Hysteresis loss risk, permanent magnet losses, rotor-surface-magnet permanent magnet machines.

I. NOMENCLATURE

B<sub>j</sub> Remanent flux density of permanent magnet, [T]
B<sub>s</sub> Stator slot opening, [m]
r<sub>r</sub> Rotor outer radius, [m]
r<sub>i</sub> Rotor inner radius, [m]
m Number of phases
n Rotational speed, [rpm]
p Number of pole pairs
Q<sub>r</sub> Number of stator slots
N<sub>p</sub> Number of series turns in the coil
μ<sub>rel</sub> Relative permanent magnet width
d<sub>c</sub> Effective airgap, [m]
μ<sub>v</sub> Permeability of vacuum, 4π x 10<sup>-7</sup> [H/m]
μ<sub>e</sub> Relative permeability of permanent magnet

II. INTRODUCTION

The ability of PMs to provide excitation without an external source of energy allows avoiding Joule losses in the excitation winding and, thus, increasing the efficiency of permanent magnet synchronous machines (PMSM) compared to the efficiencies of other machine types of similar power [1]. PMSMs are widely utilized in the industry [1], in wind power generation [2], in electrical vehicles [3]-[4], in marine propulsion, and in elevator drives [5].

Eddy current losses have been considered as the main source of losses in PMs during the normal operational mode of PMSMs. Eddy current loss models and analytical calculation of this phenomenon are widely discussed in research papers. Approaches for the eddy current loss calculation can be found, for example, in [6]-[8].

Papers [9], [10] state that in some cases a hysteresis loss is possible in PM material. The hysteresis loss mechanism is based on the hysteresis theory that is, in principle, the base theory for the PM materials. Structural defects in PM material can be considered as areas with soft magnetic properties. The presence of “soft” phases enables hysteresis loss under unfortunate operating conditions. Fig. 1 depicts the mechanism of the hysteresis loss in a PM material.

Hysteresis loss becomes possible if the magnetic field strength, which is acting on the PM material, changes its sign regularly under the machine operation [10]. In practice, the operating point of the magnet can vary between the first and the second quadrant in the B-H-demagnetization curve of the magnet. The data in [10] shows the significant effect of the armature reaction on the possibility of hysteresis losses emerging in a Rotor-Surface-Magnet (RSM) PMSMs even during the normal operational mode. Hysteresis loss can take place if the armature reaction is capable of driving the operating point of the magnet to the first quadrant of the B-H-curve and, e.g., permeance harmonics modulate the flux density below and over the remanent flux density in some regions of the magnet. This situation is possible e.g. in PMSM applications that require high torque/power density [1], [10], [11].

Existing analytical approaches are derived based on certain assumptions that can limit the application of models in hysteresis loss risk calculation. The assumptions can include, for example, infinite permeability of iron, neglecting of PM edge leakage flux, assuming sinusoidal phase currents. The aim of the paper is to show the main factors affecting the hysteresis loss risk emergence. FEM simulations and 2-D slotless analytical model with permeance function are used for calculation of the magnetic...
field distribution in the PM region. Results are compared to observe possible sources of inaccuracies caused by assumptions in the model.

III. METHODS

A. Existing analytical approaches

The present analytical methods can be divided into 3 main categories: 1) Equivalent Circuit Method (ECM), 2) Subdomain models, 3) 2-D slotless models.

ECM was successfully used for induction motors (IM) and electrically excited machines’ analysis [12]. In PM machines this method was applied in the prediction of cogging torque, unbalanced magnetic pull and some other basic performances [13], [14]. However, the relatively large effective air gap in PMSMs compared to IMs and other electrically excited machines results in a significant error in the prediction of the magnetic field distribution inside PM [12], [15].

Subdomain models are the most accurate existing analytical approaches available nowadays if the assumption of constant iron permeability is not critical [12]. The idea of the method is to solve directly 2-D Laplace’s and Poisson's equations in polar coordinates for each subdomain and applying boundary conditions between subdomains. These models are used for the calculation of back-EMF, electromagnetic torque, cogging torque and unbalanced magnetic pull [12]. The main disadvantages of the subdomain models are the relative complexity of implementation, longer calculation time compared to ECM and 2-D slotless models and the assumption of infinite iron permeability.

Comparative analysis of the 2-D slotless model with equivalent circuit method (ECM) [1] and 2-D subdomain approaches [12], [16], [17] show that this type of model has the best accuracy taking into account the computational resources needed for the calculation of the field distribution in PMs and has a very straightforward implementation. In contrary to the subdomain model, the 2-D slotless model represents a set of ready solutions that can be easily programmed.

This study uses the 2-D slotless analytical model initially presented in [15], [18]-[20] and further improved in [21] to take into account relative permeability of PM \( \mu_r \) other than unity. The solution for the armature reaction field is improved to make the analysis more applicable for hysteresis loss problem. Since the observed PMSM has radially magnetized PMs, the field calculation is provided only for the radial component of the flux density. It is assumed that due to the presence of domain orientation in the PM material, only the flux density component that is aligned with the magnetization direction of the magnet can affect the hysteresis loss emergence.

The theory provided in [15], [18]-[21] allows deriving the magnetic flux density distribution in the PM region based on solving the equations of scalar magnetic potential. Laplacian equations are solved in air region to get the radial component of the magnetic flux density created by a single conductor. Quasi-Poissonian equation is used to get the field distribution inside PM. The following assumptions are made: 1) PM permeability is constant, 2) end-effects are neglected, 3) permeability of iron is infinite.

Taking into account the assumptions above, the radial component \( B_{rad} \) of the magnetic field distribution in the PM region can be presented as a linear problem:

\[
B_{rad}(r, \theta, t) = B_{rad}(r, \theta, t) + B_{arm}(r, \theta, t) \tag{1}
\]

where \( B_{rad}(r, \theta, t) \) and \( B_{arm}(r, \theta, t) \) are PM and armature reaction radial flux density components, \( A(r, \theta, t) \) is permeance function describing the slotting effect. The models for calculating of each component in (1) are depicted in Fig. 2.

Fig. 2. Models used in 2-D slotless model for calculation a) no-load magnetic flux density, b) armature reaction field, c) stator slotting effect

First, no-load flux density of PM and armature reaction field are calculated assuming slotless machine. Second, slotting effect is taken into account by multiplying the no-load flux density and armature reaction field by the slot permeance function, since the slotting effect has influence on these two components [19].

This paper studies Tooth Coil Winding (TCW) Rotor-Surface-Magnet (RSM) PMSM with external rotor topology and all equations provided are exactly for that topology. The analytical approach for other configurations of RSM PMSMs can be found in [18]-[21].

B. No-load flux density of PM

Assuming linear second-quadrant demagnetization characteristic and uniform magnetization throughout the cross section of the PM, the radial component of the magnetization vector can be calculated as follows:

\[
M_r = \sum_{r=1,3,5,...} B_r \frac{2}{\mu_0 \alpha_{PM}} \left( \frac{V \alpha_{PM}}{2} \right) \cos(\nu \theta) \tag{2}
\]

where \( \nu = 1,3,5,... \) is the harmonic order. Solution of the Poissonian equation in the PM region gives (3) (see bottom
of page) as the expression for radial no-load flux density component in PM region for external rotor; the parameter \( A_r \) used in (3) is calculated as:

\[
A_r = \begin{cases} 
  y_p & y_p \neq 1 \\
  1 & y_p = 1 
\end{cases}
\]  

\( \text{(4) } \)

The main parameters, which are determining the PM flux density, are the dimensions of PMSM and the magnetic properties of PM.

C. Armature reaction field

Mostly, analysis of flux density is provided for the airgap region, because the airgap magnetic field is mainly used to estimate the performance of the machine. However, due to the boundary conditions for two materials with different magnetic properties, the normal component of the flux density is not changing when it is passing from one region to another. In polar coordinate system, this property of flux density allows using the airgap solution for the radial flux density component also in the PM region. The model for the armature reaction proposed in this paper is based on a solution of Laplacian equation for single coil in the airgap region. The model for coil flux density calculation in case of an external rotor configuration is depicted in Fig. 2(b). Each coil conductor is represented as a thin current density sheet with width \( b_0 \) at the surface of the slotless stator. The \( \mu_{\theta} \) of page) as the expression for radial no-load flux density component in PM region for external rotor; the parameter \( A_r \) used in (3) is calculated as:

\[
A_r = \begin{cases} 
  y_p & y_p \neq 1 \\
  1 & y_p = 1 
\end{cases}
\]  

\( \text{(4) } \)

The main parameters, which are determining the PM flux density, are the dimensions of PMSM and the magnetic properties of PM.

C. Armature reaction field

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\[
B_{coil,rad}(r,\theta,t) = \frac{2\mu_0 I_K B_{f} r^2}{\pi a} \sum_{n=1,2,3, \ldots} K_{esn} K_{ps} F_n \cos(n\theta), \tag{5}
\]

where \( n = 1,2,3, \ldots, N \) is the number of series winding turns in coil, slot opening factor \( K_{esn} \), coil span \( K_{ps} \), can be described as:

\[
K_{esn} = \sin \left( \frac{y_p b_0}{2r_c} \right), \tag{6}
\]

\[
K_{ps} = \left( \frac{y_p b_0}{2r_c} \right), \tag{7}
\]

\[
F_n = -\delta_{n1} \frac{\nu}{\rho} \frac{\nu^2}{\omega^2}, \tag{8}
\]

where \( r_m \leq r \leq r_1 \) is radius where the magnetic flux density is calculated. The coefficient \( \alpha_n \) is determining actual coil span. In case of analyzed motor \( a_p = 2\pi l Q_s \), mechanical radians. The effective airgap length \( \delta_a \) will be defined in the next subsection.

![Fig. 3. Winding configuration of TCW PMSM under observation. Due to symmetry, only half of winding is depicted.](image)

The winding configuration of the observed machine is depicted in Fig. 3. Application of (5)-(8) to actual winding topology of machine under observation results in (9) (see bottom of next page), where \( n = 0,1,2, \ldots, n = 1,2,3, n = 1,2 \) and \( i(t) \) is instantaneous value of phase current in each phase. In case of sinusoidal phase currents:

\[
i(t) = I_\text{s} \sin \left( \frac{2\pi t}{3} + \frac{2\pi}{3} n \cdot t \right), \tag{10}
\]

Eq. (9) is appropriate only for winding configuration depicted in Fig. 3. However, (6)-(9) allow creating the same model for other winding configurations. In contrary to mathematical approach used in [18] and [21], the proposed model for the armature reaction using a combination of (6)-
(9) do not need spectrum analysis of phase current and winding case and the slot pitch and 1 when winding pitch is an odd integer of the slot pitch and 1 when winding pitch is an even integer of the slot pitch; \( h_i = \delta_{\text{tooth pitch}}, K_c = \tau_i - \gamma \delta_{\text{air}} \) is stator tooth pitch, \( K_c = \tau_i - \gamma \delta_{\text{air}} \) is stator tooth pitch, \( \delta_{\text{air}} \) is airgap length to the slot pitch [19].

D. Stator slotting effect

Permeance function for the slotting effect is based on conformal mapping technique that is applied to idealized single-slot model [19]:

\[
A(f,r) = \frac{1}{K_c} \left[ 1 - \frac{\beta \delta_{\text{air}}}{\tau_i} \right] + \sum_{n=1,3,5,\ldots} \left[ \frac{4\beta \cdot \lambda_{2n} r_i^2}{\text{ax}} \left( 0.5 + \frac{h_i^2}{0.78125 b_i^2} \right) \sin \left( \delta_{\text{air}} \right) \right] \text{ln} \left( \frac{h_i}{r_i} \right), \quad (11)
\]

where \( i = 1,2,3,\ldots \), \( \lambda_i = (-1)^i \) when the winding pitch is an odd integer of the slot pitch and 1 when winding pitch is an even integer of the slot pitch; \( h_i = \delta_{\text{tooth pitch}}, \tau_i = 2\pi r_i Q_i \) is stator tooth pitch, \( K_c = \tau_i - \gamma \delta_{\text{air}} \) is stator tooth pitch, \( \delta_{\text{air}} \) is case in of external rotor topology is:

\[
\delta_{\text{air}} = (r_m - r_a) \cdot \left( \frac{r_m - r_a}{\mu_i} \right), \quad (12)
\]

and

\[
\gamma = \frac{\beta h_i}{2\delta_{\text{air}}} \text{tan}^{-1} \left( \frac{h_i}{2\delta_{\text{air}}} \right) \text{ln} \left( 1 + \frac{h_i}{2\delta_{\text{air}}} \right)^2, \quad (13)
\]

Because of slotted stator, \( r_a \) should be used further instead of \( r_i \):

\[
r_a = r_i - (K_c - 1) \cdot \delta_{\text{air}}. \quad (14)
\]

Coefficient \( \beta \) is determined as following:

\[
\beta = \frac{1}{2} \left[ 1 - \frac{1}{\sqrt{1 + \left( \frac{h_i}{2\delta_{\text{air}}} \right)^2}} \right] b^2, \quad (15)
\]

\( b \) is determined from solving equation:

\[
B_{\text{arm}} = \sum_{n=1,3,5,\ldots} \sum_{i=1,3,5,\ldots} \sum_{j=1,3,5,\ldots} \frac{2\mu_0 N_{\text{coil}} (i)}{\delta_{\text{air}}} \left[ \frac{(-1)^i \theta_{1}}{\left( 1 - \frac{\gamma}{3} \right)^2} \right] K_{\text{arm}} K_{\text{pm}} F_s \left[ \text{tan}^{-1} \left( \frac{2\pi \theta_{1}}{\theta_{2}} - 1 \right) \theta_{1} - 4\pi m \mathbf{u} \cdot \mathbf{v} - \frac{\pi \theta_{1}}{3} \right] \left( \frac{\theta_{1}}{\theta_{2}} \right) \quad (9)
\]

E. Rotor reference frame

In order to simplify further analysis, (1) is written in the rotor reference frame. After modification, (1) becomes:

\[
\begin{align*}
B_{\text{rot}} (r, \theta, t) &= B_{\text{rot}} (r, \theta, t) A(r, \theta + \Omega_t t - \alpha, t) \\
&+ B_{\text{rot}} (r, \theta + \Omega_t t - \alpha, t) A(r, \theta + \Omega_t t - \alpha, t) \quad (19)
\end{align*}
\]

where \( \Omega_t = 2\pi f_0 / \rho \) is rotor mechanical angular velocity and \( \alpha \) is rotor position at time \( t = 0 \).

The usage of rotor reference frame is significantly simplify analysis, since fluctuation of operating point in each PM can be observed individually in different moments of time.

IV. RESULTS

The analysis is provided for TCW RSM PMSM initially presented in [22]. The prototype was designed as generator for hybrid vehicle application. The parameters of the observed machine are presented in Table I. The magnetic flux density of PMSM is calculated in the top (close to air gap), in the middle and in the bottom (close to rotor hub) of PM when machine runs with frequency converter.

### TABLE I

PARAMETERS AND DIMENSIONS OF THE OBSERVED TCW RSM PMSM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power ( P_r ), [W]</td>
<td>50000</td>
</tr>
<tr>
<td>Rated torque ( T_r ), [N\cdot m]</td>
<td>159</td>
</tr>
<tr>
<td>Rated stator current ( I_s ), [Amps]</td>
<td>83.8</td>
</tr>
<tr>
<td>Rated speed ( n_r ), [rpm]</td>
<td>3000</td>
</tr>
<tr>
<td>Permanent magnet remanence ( B_r ), [T]</td>
<td>0.34</td>
</tr>
<tr>
<td>Relative permeability of permanent magnet, ( \mu_r )</td>
<td>1.26</td>
</tr>
<tr>
<td>Number of stator slots ( Q_s )</td>
<td>24</td>
</tr>
<tr>
<td>Number of pole pairs ( p )</td>
<td>10</td>
</tr>
<tr>
<td>Permanent magnet height, [m]</td>
<td>0.017</td>
</tr>
<tr>
<td>Stator outer radius ( r_m ), [m]</td>
<td>0.169</td>
</tr>
<tr>
<td>Rotor inner radius ( r_c ), [m]</td>
<td>0.187</td>
</tr>
<tr>
<td>Permanent magnet inner radius ( r_a ), [m]</td>
<td>0.170</td>
</tr>
<tr>
<td>Converter output frequency, [Hz]</td>
<td>500</td>
</tr>
<tr>
<td>Number of turns in series per one coil ( N )</td>
<td>10</td>
</tr>
</tbody>
</table>
The measured converter’s current waveforms are depicted in Fig. 4. The operation of a PMSM in frequency converter supply has a number of drawbacks, such as increasing of torque ripple, increased iron and PM losses. Permeance harmonics produced by slotting effect and non-sinusoidal distribution of windings in the stator have the highest effect on loss production in PM material when a PMSM operates with sinusoidal currents [2]. The simulation results in [2] clearly show that frequency converter caused current harmonics can dramatically increase eddy current losses in PMs and even lead to their partial permanent demagnetization. However, a high electrical resistance of Ferrite material makes eddy currents almost negligible [22]. In case of NdFeB and SmCo magnets, e.g. magnetic materials with relatively low electrical resistivity, the limitation of eddy current loss can be achieved by segmentation of PMs [2].

Figs. 5-8 depict the magnetic flux density distribution calculated with FEM and analytical model during the time of one slot transition. The selected time clearly shows the main factors affecting hysteresis loss emergence.

A. Slotting effect

Figs. 5-6 show that the slotting effect has the highest influence on the permeance harmonics in TCW PMSMs. The reason for that is the relatively large distance between two adjacent teeth in TCW compared with Distributed Winding (DW) machines. Figs. 7-8 depicts the magnetic flux density distribution in the middle and on the bottom (close to rotor hub) of the PM, respectively. The remanent flux density of the PMs used in the PMSM observed is 0.34 T. Thus, it is seen from Figs. 5-8 that significant part of the PM has the magnetic flux density variation between the 2nd and the 1st quadrant, mainly due to stator slotting caused permeance harmonics.
Stator slotting has the strongest effect close to the airgap and the effect decreases significantly when approaching the rotor hub. This shows that the assumption about constant slotting effect within all height of PM will result in a higher value of hysteresis loss estimate.

PM edge leakage flux phenomenon is also present in PMs. It can be accurately calculated with using both 2-D slotless analytical and subdomain models, however, the application of ECM approach can result in inaccuracy. Moreover, ECM model requires knowing the flux paths to be able to create an equivalent circuit.

Measurement data in [23] shows that the amplitude of the flux density variation has the highest influence on the resulting emerging losses. Thus, the slotting effect causes the major part of possible hysteresis loss. The 2-D slotless model presented in this paper is able to take into account the slotting effect with a separate multiplication function. However, the simplified slot geometry in (11)-(18) neglects the tooth tip leakage flux phenomenon. The analytical approach using complex relative permeance function [24] shows more accurate results for the slotting effect compared to (11)-(18). Nevertheless, it requires a numerical solution for each point and, thus, significantly increases the calculation time needed [12]. Subdomain models [12], [16] also demonstrate more accurate results for the slotting effect but the analysis is typically provided only for no-load magnetic flux density and is not suitable for the hysteresis loss evaluation. The analytical approach in [16] demonstrates perfect agreement with FEM results for the armature reaction field when it is observed separately from the PM-generated field. Similar accuracy was obtained with the application of (9) during separate analysis of the armature reaction field. In fact, the accuracy of the analytical approaches is dramatically reduced by the presence of teeth saturation.

B. Teeth saturation

The assumption about infinite permeability of iron in ECM-based, slotless and subdomain models simplifies the analysis, but also leads to a lower accuracy compared to FEM results. It is clearly seen in Figs. 5-6 that the assumption of iron infinite permeability will cause losing additional fluctuations of magnetic flux density and, thus, result in a lower value of calculated hysteresis loss. However, the combination of 2-D slotless analytical model with EMC model [25] provided for axial flux PMSM has no assumption about infinite iron permeability and shows good agreement with FEM results. Figs. 5-8 show that the highest inaccuracy between the model and FEM results is possible in the part of PM that is closest to the airgap. The effects of teeth saturation and tooth tip leakage flux are decreasing when approaching the rotor yoke and the slotting effect together with supply current harmonics effect become dominating factors that cause the permeance harmonic modulation.

C. Inverter harmonics

The effect of frequency converter on the magnetic flux density can be seen (small flux density fluctuations) in Figs. 5-8. Experimentally measured current waveforms in Fig. 4 were used for simulation both in the model and in the FEM program. Current harmonics cause small ripples of the flux density compared to the slotting effect, and thus, create insignificant part of total hysteresis loss. The slotting effect caused fluctuations remains the dominating factor causing hysteresis loss in TCW PMSMs. However, the relatively small distance between adjacent teeth in DW PMSMs cause smaller fluctuations of magnetic flux density due to slotting. The effect of current harmonics can be larger in DW PMSMs compared to TCW PMSMs.

D. Ways to limit PM hysteresis loss

The measurement results provided in [23] show that the hysteresis loops are non-symmetrical with respect to the $B$-axis and the $BH$-curve. The losses created by the same magnitude of flux density variation can differ significantly depending on the position of the operating point on the $BH$-curve. In fact, the hysteresis loss will be almost negligible when the magnetic flux density of PM is located in the second quadrant of the demagnetization curve [23].

Based on the analysis provided in this paper and measurement data in [23], the following design efforts will limit hysteresis loss: 1) select the dimensions of PMSM in such a way that the magnetic flux density in PM does not exceed $B_r$ during operation; 2) application of semi-magnetic wedges. The effectiveness of the proposed efforts requires further research.
V. Conclusion
Factors affecting the hysteresis loss risk in rotor-surface-magnet PMSMs were studied by analytical means and finite element analysis. To get accurate results conventional 2-D slotless analytical models need to be complemented by iron saturation phenomenon modelling. This will allow creating fast and accurate tool for magnetic field calculation that further can be a part of reliable analytical hysteresis model.

Slotting effect is the dominant hysteresis causing phenomenon in TCW PMSMs. However, phase current harmonics can be a significant source of extra hysteresis loss in DW PMSMs. The assumption about constant relative permeability of PM limits the application of present FEM-based programs and analytical models for direct hysteresis loss calculation. The further research is needed to evaluate hysteresis loss.

VI. REFERENCES


VII. BIOGRAPHIES

Dmitry Egorov received the B.Sc. degree from Moscow Power Engineering Institute (MPEI), Moscow, Russia, in 2013 and the M.Sc. degree in Electrical Engineering from Lappeenranta University of Technology (LUT), Lappeenranta, Finland, in 2015. He is currently a Doctoral Student in the Department of Electrical Engineering, LUT.

Nikita Uzhegov (M’14) received D.Sc. degree in 2016 from Lappeenranta University of Technology (LUT), Finland. He is currently a fellow researcher in the Department of Electrical Engineering, LUT.

Ilya Petrov received D.Sc. degree in 2015 from Lappeenranta University of Technology (LUT), Finland. He is currently a fellow researcher in the Department of Electrical Engineering, LUT.

JUHA J. PYRHÖNEN (M’06) born in 1957 in Kuusankoski, Finland, received the Doctor of Science (D.Sc.) degree from Lappeenranta University of Technology (LUT), Finland in 1991. He became Professor of Electrical Machines and Drives in 1997 at LUT. He is engaged in research and development of electric motors and power-electronic-controlled drives. Prof. Pyrhönen has wide experience in the research and development of special electric drives for distributed power production, traction drives and high-speed applications. Permanent magnet materials and applying them in machines have an important role in his research. Currently he is also researching new carbon-based materials for electrical machines.
Publication II

Petrov, I., Egorov, D., Link, J., Stern, R., Ruoho, S., and Pyrhönen, J.

Hysteresis losses in different types of permanent magnets used in PMSMs

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Hysteresis Losses in Different Types of Permanent Magnets Used in PMSMs

Ilya Petrov, Dmitry Egorov, Joosep Link, Raivo Stern, Sami Ruoho, Member, IEEE, and Juha Pyrhonen, Member, IEEE

Abstract—In permanent magnet synchronous machines (PMSM), depending on the machine application, different types of permanent magnets (PM) can be used. The most common PMs are ferrite magnets, neodymium iron boron magnets (NdFeB), and samarium cobalt magnets (SmCo). The selection of a suitable magnet for a particular machine design depends on the magnet properties: remanence, conductivity, magnetic rigidity, losses, and demagnetization characteristics. Usually, the possibility of hysteresis losses in PM materials is neglected. In this paper, however, it is demonstrated that possible hysteresis losses have to be evaluated in the machine design. It is shown by measurements and simulations that in some machine designs, hysteresis losses in NdFeB, SmCo, and ferrite magnets can be a source of significant additional ac losses that may lead to too high PM operating temperatures and a reduction in the machine efficiency.

Index Terms—Ferrite magnets, hysteresis losses, neodymium magnets, permanent-magnet machines, samarium cobalt magnets.

I. INTRODUCTION

PERMANENT magnets (PMs) have been used in electrical machines since the first half of the 20th century [1]. Until samarium cobalt magnets and neodymium magnets were invented, only ferrite magnets and AlNiCo were available in the market. The energy densities of these magnets were relatively low, and their demagnetization risk was high. Therefore, ferrite and AlNiCo magnets were not used widely in high-power (tens of kW) industrial applications. However, the penetration of PM technology into the field of high-power high-torque electrical machines was boosted by the invention of samarium cobalt magnets [2] and neodymium magnets [3]. The high energy product together with satisfactory demagnetization properties allowed the use of PMs even in challenging applications such as direct-drive wind-power generators [4], [5] and propulsion motor drives in hybrid vehicles [6], [7].

In principle, the implementation of PM technology in electrical machines eliminates the losses related to the excitation field generation. Thus, it can be expected that the efficiency of an appropriately designed permanent-magnet synchronous machine (PMSM) should be higher compared with electrical machines of the same size without PMs (e.g., induction motor, synchronous machine, switched reluctance machine, synchronous reluctance machine, dc machine) [8]–[10]. Therefore, application of PM technology is constantly increasing in electrical machines for different purposes.

Recently, in some electrical machine designs, a phenomenon related to PMs hysteresis losses was observed. The origin of the phenomenon was explained in [11]. The machine operating point at which the hysteresis losses in PMs occur was also shown in [11]. However, no clear picture of the amount of hysteresis losses in the magnets has been given (e.g., the energy of hysteresis loops at different magnetic field strengths), and no method for the estimation of hysteresis losses in a PMSM has been shown so far. This paper should fill this gap. Three different PM types (NdFeB, SmCo, and ferrite magnets) are analyzed in terms of hysteresis losses, and the possible PMSM efficiency reduction resulting from the hysteresis losses is assessed. Parameters of the PMs analyzed in this paper are listed in Table I.

The paper is organized as follows. In Section II, the origin of hysteresis losses in PMs is described and the measured results are introduced. In Section III, the influence of a PMSM construction on hysteresis losses in different PM types is evaluated. A comparison between the hysteresis losses in different PM types applied in similar PMSMs is provided. Section IV concludes the paper.

II. HYSTERESIS LOSSES IN PMs

A. Reasons for Hysteresis Losses

PMs with a relative permeability of $\mu_r > 1$ are prone to hysteresis losses, if the PM flux density varies over and under the remanent flux density because of the armature reaction and permeance modulation in the operating point [11]. For the sake of completeness, the reasons for this phenomenon are described in brief in this section. Fig. 1 shows the idealized hysteresis loop of the PM (in the first and the second quadrants) including the


**TABLE I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NdFeB</th>
<th>SmCo</th>
<th>Ferrite magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_r$ [T]</td>
<td>1.1</td>
<td>1.11</td>
<td>0.38</td>
</tr>
<tr>
<td>$H_cB$ [kA/m]</td>
<td>830</td>
<td>822</td>
<td>280</td>
</tr>
<tr>
<td>$H_cJ$ [kJ/m³]</td>
<td>225</td>
<td>250</td>
<td>29</td>
</tr>
<tr>
<td>$\mu_r$</td>
<td>1.07</td>
<td>1.09</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Fig. 1. Idealized hysteresis loop of the PM (in the first and the second quadrants). It includes two small hysteresis loops of magnetically soft magnet areas. However, in an actual PM, the number of hysteresis loops may be large (depending on the number or type of magnetically soft PM material areas), and the total hysteresis loop of the PM would be somewhat smoother.

Fig. 2. Estimation of the energy in one hysteresis loop (hysteresis area) of a PM.

Fig. 3. (a) Test bench for measurement of magnets $BH$ curves consists of a physical properties measurement system with up to 14 Tesla superconducting magnet from Quantum Design with a PS25 VSM and data acquisition system. (b) Sample size of the PM used for the measurement procedure.

hysteresis loops of the magnetically soft magnet areas. In the figure, two hysteresis loops for the magnetically soft magnet areas are illustrated with different $BH$ curves. However, in reality, there may be numerous types of magnetically soft magnet areas with different hysteresis loops. It means that the actual resultant hysteresis loop of the magnetically soft magnet areas can be smooth rather than discrete as it is shown in Fig. 1.

In Fig. 1 it can be seen that if the PM flux density exceeds the magnet remanent flux density (1 → 2), some of the magnetically soft magnet areas are magnetized and the total PM magnetization increases (2 → 3). If the PM flux density is further increased (3 → 4), other magnetically soft magnet areas are magnetized and the PM magnetization reaches its maximum value (4 → 5). However, if the PM flux density returns back to the operating point in the second quadrant (5 → 6 → 7 → 8 → 1), the magnetically soft magnet areas are demagnetized and the total PM magnetization reduces. This explains the appearance of hysteresis loops in the PMs when the PM flux density exceeds the remanent magnet flux density.

**B. Hysteresis Specific Energy of PMs**

The actual magnetic losses caused by these hysteresis loops of the magnetically soft magnet areas are determined by the amplitude of the variable field strength applied to the magnets, the quantity of the magnetically soft magnet areas, and the behavior of these magnetically soft magnet areas. These characteristics depend on the quality of magnets and may vary in different magnets (magnet type, magnet grade, manufacturer). When the hysteresis loop is measured, it is possible to find the energy that this loop includes, as it is shown in Fig. 2. If the hysteresis loop is known, it is possible to integrate its upper and lower lines over the applied field strength (e.g., $-380$ to $380$ kA/m). After that, the total hysteresis specific energy $[J/m^3]$ can be found as

$$E_{hyst} = \int_{H_{min}}^{H_{max}} B_{up}(H) dH - \int_{H_{min}}^{H_{max}} B_{low}(H) dH$$  \hspace{1cm} (1)

where $B_{up}$ represents the upper line and $B_{low}$ represents the lower line of the hysteresis loop.

In order to observe the possible difference in hysteresis loops of the PMs with different structures, it was decided to measure the actual hysteresis loops of samples of most common PM types and estimate the possible hysteresis losses for ferrite PM, NdFeB, and SmCo. The photograph of the test bench used for measurements of the PMs $BH$ curves in a wide field strength range (while keeping the measurement precision in acceptable level) is shown in Fig. 3(a). Approximate size of the samples used for the measurements is shown in Fig. 3(b).

The measurement procedure includes field strength variation with recording of the PM magnetization in a similar manner as it was done in [11]. The field strength variation was applied with
different extreme values to investigate the influence of hysteresis losses on the external field strength. Further, the influence of the field strength alternation only in one (second) quadrant on the hysteresis losses was observed. No irreversible demagnetization point was reached during the measurements of the hysteresis loops. It means that the hysteresis losses do not include energy, which would be required for irreversible demagnetization or magnetization of the magnets.

The vibrating sample magnetometer (VSM) shown in Fig. 3(a) used an open-circuit measurement system. This means that there is a self-demagnetization field \( H_d \) in a PM as it is shown in Fig. 4(a). The self-demagnetization field contributes to the total magnet field as shown in Fig. 4(b) and (c). Therefore, the self-demagnetization field of the open circuit should be taken into account and a proper correction of the applied field \( H_{app} \) should be made to find the actual internal magnet field \( H_{int} \).

The value of self-demagnetization field can be estimated if the permeance coefficient is known, whereas the permeance coefficient of a magnet sample with rectangular shape can be estimated by [12]

\[
k_\Lambda = \frac{1}{77} \frac{h}{l w} \left( \frac{1}{h(l+w)} + \frac{1}{l w} \right)
\]

where \( h \) is the height of magnet (the height is along the magnetization direction), \( l \) is the length of the magnet, and \( w \) is the width of the magnet.

Based on the permeance coefficient, the demagnetization factor can be estimated by

\[
N_d = \frac{1}{(k_\Lambda + 1)}
\]

and finally the self demagnetization field can be found for each magnet sample by

\[
H_d = -J N_d \mu_0
\]

where \( J \) is the magnetic polarization of the magnet and \( \mu_0 \) is the permeability of vacuum.

The actual internal field in the magnet during the open-circuit measurement procedure should be found by correction of the applied field with the demagnetization field. The illustrated figures shown hereafter with magnets hysteresis loops already include this correction. Thereby, they comprise only internal magnet field.

C. Hysteresis Loop Shapes of PMs at Different Field Strengths

Fig. 5 shows the hysteresis loops in a neodymium magnet similar to the one analyzed in [11]. The hysteresis loops shown in the figure with different field strength amplitudes differ significantly from each other with regard to the magnetic energy value. The highest energy losses can be found in the hysteresis loop that exceeds the remanent flux density and which has the highest field strength variation, as it was expected earlier. However, an additional phenomenon can be observed in Fig. 5, which is the different slope angles of the hysteresis loops with different applied field strengths. The different slopes of the hysteresis loops with a higher applied field strength can be explained by irreversible demagnetization of the magnetically soft magnet areas at higher negative field strengths, whereas the magnetization of these magnetically soft magnet areas occurs only partially because no strong enough positive magnetic field is applied. Therefore, the remanent flux density decreases when a higher negative field strength is applied starting from the initial complete magnetization of the magnet as it is shown in Fig. 6. This figure comprises the following procedure: after complete magnetization of the neodymium magnet (where all magnetically soft areas are magnetized), a fairly high negative field strength
of \(-650\) kA/m corresponding to opening of the PM circuit is applied. At this negative field strength, the magnetically soft areas are demagnetized (curve 1) and the magnet has, in principle, attained its operating performance. The next step is to vary the field strength between \(-250\) and \(-50\) kA/m (curve 2) describing a possible hysteresis behavior under armature reaction and modulation by permeance harmonics. With this field strength none of the magnetically soft areas are magnetized or demagnetized. Finally, the field strength varies between \(-470\) and \(+100\) kA/m (curve 3). In this curve, we can clearly see the magnetization and demagnetization of the part of magnetically soft areas, which represents the actual possibility of having considerable hysteresis losses in PMs if the flux density in the magnet repeatedly exceeds the critical flux density. This critical flux density for different types of PMs can vary, but it is usually found close to zero magnetic field strength. The similar phenomenon was also observed in [13].

The BH curves of the SmCo magnet at different applied field strengths are shown in Fig. 7. The figure shows that the hysteresis loops of the magnet that do not exceed the remanent flux density contain less energy than those which exceed the remanent flux density. The ferrite magnet is not fully magnetized in order to exclude the possible partial irreversible demagnetization in the hysteresis loops at a high applied field strength (normally magnetized remanent flux density, at \(T = +23^\circ C\) is \(B_{\text{rem}} = 0.38\) T).

When a machine with ferrite magnets is designed, it is usually assumed that no losses take place in the PMs, because ferrite magnets have a very high electric resistivity, which prevents any practical eddy current losses [14]. However, if the armature reaction is strong enough, the hysteresis losses can be significant in some machine design. This can have a negative effect on the motor efficiency. Therefore, the influence of the described phenomenon on the actual PM losses and consequently, on the machine efficiency should be estimated. The estimation methods and the results are described in the following section.

III. FEA-BASED EVALUATION OF ADDITIONAL AC LOSSES CAUSED BY PM HYSTERESIS LOSSES IN A PMSM

A. Influence of the PM type on the Motor Parameters, Including PM Hysteresis Losses

At the beginning of a PMSM design process, a suitable PM type should be selected. The selection is based on the magnet properties required for a certain PMSM design. For example, in rotor surface magnet PMSMs, the no-load air gap flux density is determined by the remanent flux density and the magnetic circuit reluctance. As a result of the magnetic flux density, the pole cross-sectional surface, and the number of effective stator winding turns, a suitable back electromotive force (EMF) is induced. The number of turns and the pole pair number have an influence on the synchronous inductance \((L_s \approx N^2, L_s \approx 1/p^2)\) of the machine [15]. The synchronous inductance indicates how much magnetic flux linkage is produced by a certain armature phase current. This magnetic flux linkage (armature reaction) may significantly contribute to the resultant magnetic condition of the machine, which at no load is only affected by the PM flux. If the low air-gap flux density effects in a PMSM with ferrite magnets are compensated by a higher electrical loading (linear current
density) to achieve a tangential stress even close to the levels of PMSMs with neodymium magnets, the armature reaction can be much more essential than in a machine construction with strong (neodymium) magnets. Knowing the actual air gap flux density and the required tangential stress, the linear current density $\hat{A}$ can be estimated by

$$\hat{A} = \frac{2\sigma F}{\hat{B}_1 \cos \phi}$$  (5)

where $\sigma F$ is the tangential stress, $\hat{B}_1$ is the peak air gap flux density of the working harmonic, and $\phi$ is the phase shift angle between the linear current density and the air gap flux density.

Rare-earth PMs should be used in machines in which it is advantageous to have a high air gap flux density with the lowest possible machine weight. Otherwise, if the cost of the machine is an important factor, ferrite magnets could be used [14]. However, because of the low air gap flux density when rotor surface ferrite magnets are the only source of the excitation field, a higher number of stator winding turns is required to induce the same back EMF as in the case of stronger PMs. This means that if the current density is kept unchanged, the phase resistance increases proportionally with the number of turns (length of the conductor), and consequently, the copper Joule losses increase. Therefore, it is expected that a machine with weaker PMs should have a lower efficiency than its counterpart with stronger magnets. However, according to the above, an additional negative effect of using weaker magnets may appear; that is, hysteresis losses. This means that when low-cost and weaker magnets are used instead of stronger magnets, the efficiency degradation is not only due to the stator copper losses, but also to the higher hysteresis losses in the magnets, which should be taken into account when the PM type is selected as it will be shown below.

B. Description of PMSMs Used as an Example to Determine the PM Hysteresis Losses

For a fair comparison of the hysteresis losses of three different PM types (ferrite PM, NdFeB, SmCo), the same PMSM construction was used in all three cases; an outer rotor tooth coil winding (TCW) PMSM with rotor surface PMs with the same geometry dimensions. The only part that was modified for each case is the stator tooth width to keep the peak flux density in the teeth at 1.6 T. This particular PMSM construction with an outer rotor and rotor surface PMs is based on an actual machine prototype with ferrite magnets, which was developed and constructed as a generator for a hybrid electrical bus [16]. In the tests of the TCW PMSM, it was found that its efficiency at the nominal load is lower than expected. This is partly explained by additional ac losses in the stator windings produced by strand-level and bunch-level circulating currents [17], [18]. However, a source of a large proportion of the losses has thus far been unknown. Therefore, it was decided to analyze whether the ferrite magnets are prone to hysteresis losses, because during the machine design it was assumed that no losses take place in the magnets as a result of their high resistivity, which, however, does not have an impact on the possible hysteresis losses.

The simplified constructions of the machines with different magnets are illustrated in Fig. 9. The main parameters of the PMSMs are listed in Table II. In Fig. 9, we can see that in the case of rare-earth magnets, the PM flux density does not exceed the remanence at the nominal load. In the case of ferrite magnets instead, the armature reaction is sufficient to increase the PM flux density beyond its remanence. It can be assumed that no significant hysteresis losses take place in this PMSM construction type if rare-earth magnets are used. This assumption is, however, not valid for the case of the PMSM with ferrite magnets, which can be prone to PM hysteresis losses.

C. Evaluation and Comparison of Hysteresis Losses in Different PM Types Applied in a PMSM

It was assumed (during the FEM simulations) that the permeability of the PMs is constant (the one which is in the second...
Table II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NdFeB</th>
<th>SmCo</th>
<th>Ferrite magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal torque ( T ) [Nm]</td>
<td>180</td>
<td>198</td>
<td>122</td>
</tr>
<tr>
<td>Nominal speed ( n ) [rpm]</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>Number of slots ( Q )</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Number of pole pairs ( p )</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Current density ( J ) [A/mm²]</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Number of winding turns ( N )</td>
<td>288</td>
<td>336</td>
<td>864</td>
</tr>
<tr>
<td>Linear current density ( A ) [A/mm²]</td>
<td>27</td>
<td>16.5</td>
<td>61.7</td>
</tr>
<tr>
<td>Stator tooth width ( b_2 ) [mm]</td>
<td>22.4</td>
<td>19.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Stator core outer diam. ( D_2 ) [mm]</td>
<td>340</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td>PM remanence ( B_{rem} ) [T]</td>
<td>1.15</td>
<td>1.0</td>
<td>0.37</td>
</tr>
<tr>
<td>PM relative permeability ( \mu_r )</td>
<td>1.05</td>
<td>1.05</td>
<td>1.15</td>
</tr>
<tr>
<td>PM height ( h_{PM} ) [mm]</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Air gap length ( \delta ) [mm]</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Back EMF ( E_{ph} ) [Vrms]</td>
<td>230</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>Phase current ( I_{ph} ) [Arms]</td>
<td>8.3</td>
<td>9.1</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The effects of armature reaction on the flux density distribution in the air gap of the PMSMs analyzed with different magnets are shown in Fig. 10, where the flux density distributions curves are illustrated in the air gap along the PM, which is subjected to the maximum armature reaction at the nominal load. In the figure, we can see that in the case of ferrite magnets there is a local region where the air gap flux density exceeds the ferrite magnet remanence because of the armature reaction. This local region of the PM is expected to be prone to hysteresis losses at the nominal load. The rest of the PM (right part in Fig. 10) instead remains in the second quadrant of the \( BH \) curve, which means that no practical hysteresis losses take place in this region.

As it is shown in Figs. 9 and 10, not the whole ferrite magnet is prone to hysteresis losses but only the part where the PM flux density exceeds the remanent flux density and, on the other hand, is modulated by permeance or current linkage harmonics.

In order to estimate an exact PM region that can be prone to hysteresis losses, the PM was divided into several regions. Each region is analyzed separately as it is shown in Fig. 11. The flux density in each point shown in Fig. 11 can be estimated as a function of time (or as function of PM region position during the rotor movement) at the nominal load.

The actual PM shown in Fig. 9(c) was divided into 4200 regions (seven layers along the PM height and 600 layers along the PM width). The high number of regions is used to reduce the margin of error resulting from the discrete nature of the analysis. When the flux density variation in each region is known after the simulation during one slot period, it is possible to evaluate how these regions are exposed to hysteresis losses. The PMSM with ferrite magnets shown in Fig. 9(c) was used for evaluation of the hysteresis losses at the nominal load. The ferrite magnet used in the PMSM is the same to the one whose hysteresis losses were measured, Fig. 8.

Because only two \( BH \) curves were measured during the ferrite magnet hysteresis loss measurements in Fig. 8 (with 2229...
and 606 J/m³), it was decided to use only these values for the PM regions that are prone to hysteresis losses (if the simulated extreme values exceed measured ones shown in Fig. 8). The resultant regions of the ferrite magnet that can be prone to hysteresis losses are shown in Fig. 12. In the figure, we can see that the PM regions that are prone to hysteresis losses are located only on one side of the PM as it was expected above.

In order to determine the total hysteresis loss during one period of flux density variation in the PM, it is necessary to sum up all volumes of the regions that have a particular hysteresis loss (e.g., 2229 J/m³) and multiply the total volume by this value of hysteresis loss as

\[ E_{\text{tot}, \text{hyst}} = E_{\text{hyst}} V_{\text{hyst}} \]  

where \( V_{\text{hyst}} \) is the total PM volume that has \( E_{\text{hyst}} \) hysteresis losses in one electrical cycle.

In the PMSM shown in Fig. 9(c), the resultant energy dissipation resulting from the hysteresis losses during one flux density period in one magnet is \( E_{\text{hyst}} = 22.6 \text{ mJ} \). Knowing the number of slots \( Q_s \), the number of PMs \( N_{\text{PM}} \) and the rotational speed \( n \), the total hysteresis losses can be estimated by

\[ P_{\text{hyst}} = E_{\text{tot}, \text{hyst}} Q_{\text{s}} N_{\text{PM}} n \]  

where \( n \) is the rotational speed [s⁻¹]. If it is assumed that the rotational speed is 3000 r/min, with the number of stator slots \( Q_s = 24 \) and the number of PMs \( N_{\text{PM}} = 2p = 20 \), the total PM hysteresis losses in the PMSM shown in Fig. 9(c) is \( P_{\text{hyst}} = 543 \text{ W} \), which is 1.4% of the nominal power of the analyzed PMSM (see Table II).

The original PMSM with ferrite magnets designed as a generator for a hybrid bus has a similar structure to the one in Fig. 9(c). However, to prevent the demagnetization risk at the nominal load, the PM height in the original PMSM was selected to be \( h_{\text{PM}} = 17 \text{ mm} \). The PM height in a PMSM with the same linear current density should have a direct influence on the PM hysteresis loss because of the different magnetic circuit reluctance and the larger amount of PM material. Fig. 13 shows the regions in the PM of the original PMSM that can be prone to hysteresis losses at the nominal load. Fig. 13 resembles Fig. 12 with the only difference that the PM regions which are prone to hysteresis losses in Fig. 13 do not penetrate through the whole PM height. This is due to the fact that with the larger PM height, the effect of the armature reaction is reduced as a result of the low PM permeability. The resultant total hysteresis losses of the original PMSM at 3000 r/min are \( P_{\text{hyst}} = 278 \text{ W} \), which is approximately half of that in the PMSM with \( h_{\text{PM}} = 8 \text{ mm} \). Thus, it can be said that it is possible to reduce the hysteresis losses in the PM if its height is increased.

D. PM Hysteresis Losses in PMSMs With Low Number of Poles

It was found earlier that the rare-earth PMs are not likely to be affected by hysteresis losses if the number of pole pairs is high (e.g., 10). However, if the number of poles is low (as, e.g., in high-speed machines), the synchronous inductance can be large enough so that the armature reaction may shift the PM flux density above its remanence in some magnet regions. In order to analyze the possible hysteresis losses in rare-earth PMs that can be used in PMSMs with a small pole number, two similar PMSMs were designed with neodymium and samarium cobalt magnets. The main parameters of the PMSMs are listed in Table III.

The effect of the armature reaction on the PM flux density in the PMSM with neodymium magnets at the nominal load is shown in Fig. 14. The figure shows that one half of the PM has the same magnetization direction as the armature reaction, whereas another half of the PM opposes the armature reaction. Therefore, we are interested in the magnet region whose magnetization coincides with the armature reaction, because this region can be prone to hysteresis losses. As in the case with ferrite magnets, only two major hysteresis loops are used for the estimation of the hysteresis losses in rare-earth magnets. For neodymium magnets they are with 2868 and 923 J/m³ (see Fig. 5), and for samarium cobalt magnets they are 6001 and 2172 J/m³ (see Fig. 7).
When comparing neodymium magnets with samarium cobalt magnets, it was also found that samarium cobalt magnets have larger hysteresis losses at a smaller field strength variation. However, to be able to claim a possible trend in these magnets, different PMs grades from different manufacturers should be tested, which is out of the scope of this paper and remains to be studied.

### IV. Conclusion

The actual hysteresis losses in PMs were found by the FEM based on the measurements of the hysteresis losses of different PM types: ferrite magnets, samarium cobalt magnets, and neodymium magnets. It was found that ferrite magnets are more prone to hysteresis losses than rare-earth PMs if the same current density in the slot and flux density in the stator tooth are applied. Therefore, in the PMSM design, when selecting the PM material, one should also consider possible hysteresis losses in the PMs.

### Table III

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NdFeB</th>
<th>SmCo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal torque F [Nm]</td>
<td>117</td>
<td>106</td>
</tr>
<tr>
<td>Nominal speed ω [rpm]</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Number of slots q</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Number of pole pairs p</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Current density j [A/mm²]</td>
<td>5.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Number of winding turns N_w</td>
<td>46</td>
<td>52</td>
</tr>
<tr>
<td>Linear current density j [A/mm²]</td>
<td>31.3</td>
<td>31.3</td>
</tr>
<tr>
<td>Stator tooth width h_s [mm]</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Stator core outer diam. D_s [mm]</td>
<td>280</td>
<td>280</td>
</tr>
<tr>
<td>PM relative permeability μr</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Air gap length l [mm]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Back EMF k [V/mm]</td>
<td>143</td>
<td>141</td>
</tr>
<tr>
<td>Phase current I_p [A/mm²]</td>
<td>8.3</td>
<td>9.1</td>
</tr>
</tbody>
</table>

When comparing neodymium magnets with samarium cobalt magnets, it was also found that samarium cobalt magnets have larger hysteresis losses at a smaller field strength variation. However, to be able to claim a possible trend in these magnets, different PMs grades from different manufacturers should be tested, which is out of the scope of this paper and remains to be studied.

### References


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**Fig. 14.** PM flux density distribution at the nominal load of the PMSM.
Ilya Petrov received the D.Sc. degree from the Lappeenranta University of Technology (LUT), Lappeenranta, Finland, in 2015. He is currently a Fellow Researcher in the Department of Electrical Engineering, LUT.

Dmitry Egorov received the B.Sc. degree from the Moscow Power Engineering Institute, Moscow, Russia, in 2013, and the M.Sc. degree in electrical engineering from the Lappeenranta University of Technology (LUT), Lappeenranta, Finland, in 2015. He is currently a Doctoral student in the Department of Electrical Engineering, LUT. His research mainly concerns electrical machines and drives, in particular, short circuits analytical modeling.

Joosep Link received the Bachelor’s degree in engineering physics from the Tallinn University of Technology, Tallinn, Estonia, in 2013, where he is currently a Master’s student. He is also an Engineer in the Department of Chemical Physics, National Institute of Chemical Physics and Biophysics, Tallinn, Estonia. His research interests include permanent magnets, multiferroics, and memristive materials.

Raivo Stern received the M.Sc. degree in condensed matter physics from Tartu University, Tartu, Estonia, and the Ph.D. (Solid State Physics) degree from Zurich University, Zürich, Switzerland, in 1987 and 1995, respectively. He is currently a Research Professor in the Department of Chemical Physics, National Institute of Chemical Physics and Biophysics (NICPB), Tallinn, Estonia, and has served since 2006, as the Director of the whole NICPB. His research interests include the field of various modern materials, in particular, quantum magnets, strong permanent magnets, memristive materials, and unconventional superconductors.

Sami Ruoho (M’10) received the M.Sc. degree in applied physics from the University of Turku, Turku, Finland, in 1997, and the D.Sc. (Technology) degree from Aalto University, Helsinki, Finland, in 2011. He has been working in the permanent magnet industry since 2002. He is currently a Managing Director of Nordmag Oy, Pori, Finland, a company offering consulting and engineering services concerning permanent magnets and PM machines. His research interests include the properties of rare earth magnets and electromagnetic and thermal modeling of electromagnetic devices.

Juha Pyrhönen (M’10) was born in Kuusankoski, Finland, in 1957. He received the Doctor of Science (D.Sc.) degree from the Lappeenranta University of Technology (LUT), Lappeenranta, Finland, in 1991. He became an Associate Professor of electrical engineering at LUT in 1993 and a Professor of electrical machines and drives in 1997. He is engaged in research and development of electric motors and electric drives. His current research interests include different synchronous machines and drives, induction motors and drives, and solid-rotor high-speed induction machines and drives.
Publication III

Egorov, D., Petrov, I.; Link, J., Stern, R., and Pyrhönen, J. J.

Model-based hysteresis loss assessment in PMSMs with ferrite magnets

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Model-Based Hysteresis Loss Assessment in PMSMs With Ferrite Magnets

Dmitry Egorov, Ilya Petrov, Joosep Link, Raivo Stern, Member, IEEE, and Juha J. Pyrhonen, Member, IEEE

Abstract—Hysteresis losses in ferrite permanent magnets (PMs) of a rotor-surface-magnet (RSM) PM synchronous machine (PMSM) were studied by means of vibrating sample magnetometer (VSM) measurements, updated static history dependent hysteresis model (HDHM) and finite element analysis (FEA). Open magnetic circuit VSM measurement results were applied to determine the magnet intrinsic properties. The HDHM developed originally for electrical steel hysteresis modeling is adopted for ferrite PM material. FEA-based results for magnetic field strength calculations both by analytical and finite element analysis (FEA) in PMs of a tooth coil winding RSM PMSM under ideal sinusoidal and frequency converter supplies were used as input data for the HDHM and the hysteresis losses were calculated in the machine’s magnets. Differently from NdFeB and SmCo PMs ferrite PMs do not seem to demonstrate significant hysteresis behavior. It was found that the hysteresis loss could be neglected in ferrite PMs in most PMSM designs if the magnet is fully polarized.

Index Terms—Ferrite magnets, hysteresis loss, permanent magnet (PM) losses, rotor-surface-magnet (RSM) permanent magnet machines.

I. INTRODUCTION

The property of permanent magnet (PM) material to produce a magnetic field without a continuous external source of energy has led to a wide usage of PMs in electrical machines designed for various purposes. In theory, the application of PMs allows us avoiding the excitation Joule loss and, thus, increasing the efficiency of an electrical machine with similar speed and power machines without PM material. However, in practice, the PM material in an electrical machine can be prone to both eddy-current and hysteresis losses [1]. The eddy current losses of sintered rare-earth magnets are widely discussed in research papers and can be calculated in the machine's magnets. Differently from NdFeB and SmCo PMs ferrite PMs do not seem to demonstrate significant hysteresis behavior. It was found that the hysteresis loss could be neglected in ferrite PMs in most PMSM designs if the magnet is fully polarized.

The hysteresis loss possibility in electrical machine PM applications is a relatively lately studied phenomenon, which has attracted attention with the increasing penetration of permanent magnet synchronous machines (PMSMs) on the market and general demands of electrical machine effectiveness. The hysteresis losses in NdFeB magnets were separated from eddy current losses by a two-frequency method and applied to the analysis of a rotor surface magnet (RSM) PMSM in [5]. The testing procedure in [5] uses magnetically short-circuited PMs that is not a normal situation in a rotating machine, which has an air gap. Therefore, the method results in overestimated hysteresis loss. The possibility of hysteresis loss was analytically observed for a traction motor and a high-speed motor in [6] and for a tooth coil winding (TCW) RSM PMSM in [7]. Finally, some hysteresis loops for NdFeB, SmCo, and ferrite PMs were measured in [1] at ambient temperature and the hysteresis losses themselves were roughly determined for an RSM PMSM based on a couple of measured loops. The measurement results for SmCo and NdFeB in [1] are provided for fully magnetized samples and clearly depict the possibility of SmCo and NdFeB PM materials having hysteresis loss during the normal operation mode of the machine in an unfortunate design case. However, the results for the ferrite PM grade were obtained for a partially demagnetized sample that is not typical for the actual usage of PMs in electrical machinery and, because of this, a misleading conclusion regarding the observed ferrite PM material was made. Thus, no appropriate investigation has been provided yet about the possible contribution of ferrite PM’s hysteresis loss in the total loss of an electrical machine during its normal operation mode.

Recently, ferrite PMs were used in high-speed electrical machines [8]. The high electrical resistivity of ferrite PM materials significantly damps possible eddy currents in this material and makes it attractive, e.g., for high-speed applications. The results in [8] depict a significant reduction of high-speed PMSM cost with very small degrading of efficiency when comparing the use of SmCo or ferrite in PMSMs. The much lower remanence of ferrite PMs compared to typical remanences of rare-earth magnets requires using a smaller airgap and despite this, a low air gap flux density will be still observed in an RSM PMSM. The low air gap flux density can be compensated by a higher linear current density in the stator. However, this leads to a higher armature reaction field. Thus, the necessary conditions for the hysteresis loss are more likely created in PMSMs with ferrite PMs than with rare-earth PMSMs [6], [9].
This paper studies the hysteresis loss in the ferrite PMs of a TCW RSM PMSM designed to work as a generator in a hybrid vehicle application [9]. High accuracy measurements, FEA simulations, and analytical modeling are used in the study. The parameters of the observed PMSM are provided in [9] and for the sake of completeness, repeated in this paper (see Section III). The paper is organized as follows. The measurements and analytical model principle are presented in Section II. Section III contains the model calculation results accounting the losses in ferrite PMs. Discussion of the results and conclusions are provided in Sections IV and V.

II. METHODS

A. Hysteresis Loss Mechanism and Measurements

The presence of soft magnetic regions in PM material enables hysteresis loss in some PMSM designs [1]. As an indication of the existence of these soft magnetic regions is the relative permeability \( \mu_r \), value of the material higher than one [6]. In present day, ferrites \( \mu_r \approx 1.05 - 1.1 \) [10], [11]. Fig. 1 depicts a typical hysteresis loop of an NdFeB magnet found by measurements provided in [1] and [6]. The measurement results for fully polarized NdFeB and SmCo PMs show that the possibility of hysteresis losses in a PM material can be detected with the steepness change of the main loop when it is crossing the \( J_H \)-axis.

The test bench is the same as was used in [1] and contains a physical properties measurement system with up to 14 T superconducting magnet developed by Quantum Design with a P525 vibrating sample magnetometer (VSM) and data acquisition system. The testing sample (BM9 ferrite PM) was cut from a physical properties measurement system with up to 14 T superconducting magnet developed by Quantum Design with a P525 vibrating sample magnetometer (VSM) and data acquisition system. The obtained polarization measurements \( J \) versus the applied field \( H_a \) represent the characteristics of a ferrite sample in a totally open magnetic circuit. The demagnetizing field emerges in a PM if an airgap is present in the PM’s magnetic circuit [10]. This field is directed against the magnetization and tries to demagnetize the PM as shown in Fig. 3. The presence of the demagnetizing field \( H_d \) results in a different shape in a VSM-measured \( JH \)-curve compared to the real or intrinsic hysteresis strength acting on the initially fully polarized sample. It is seen that both the main loop and the minor loops do not experience any clear change of the slope steepness when crossing the \( J_H \)-axis.

The result, however, indicates that there exist hysteresis loops, and therefore a possibility for hysteresis loss but the behavior of the present ferrite PM grade is different compared to the behavior of rare-earth magnets illustrated in Fig. 1.

The open circuit measurement system of VSM creates a demagnetizing field problem that will be discussed in the following section. It makes the interpretation of the measurement results somewhat complicated because the conditions of the magnet strongly differ from the conditions in a real machine and a correction in the analysis must be made.

B. Demagnetizing Field

The obtained polarization measurements \( J \) versus the applied field \( H_a \) represent the characteristics of a ferrite sample in a totally open magnetic circuit. The demagnetizing field emerges in a PM if an airgap is present in the PM’s magnetic circuit [10]. This field is directed against the magnetization and tries to demagnetize the PM as shown in Fig. 3. The presence of the demagnetizing field \( H_d \) results in a different shape in a VSM-measured \( JH \)-curve compared to the real or intrinsic hysteresis
The intrinsic susceptibility $\chi$ can be used to convert the VSM measurement results into the intrinsic hysteresis curve of the material [10]:

$$H_{ci} = H_{ci} - \frac{N_{0} I_{c}}{\mu_{0}}$$  \hspace{1cm} (1)

where $H_{ci}$ are the field strength values inside the PM, $(H_{ci}, J_{ci})$ are the measurement results from VSM, and $\mu_{0} = 4\pi \times 10^{-7}$ H/m is vacuum permeability. Assuming that the material susceptibility $\chi = \mu_{c} - 1$ is constant and close to zero, $N_{0}$ is calculated analytically for a parallelepiped formed sample with $2x \times 2y \times 2z$ $(M/F)$ being the dimensions of the sample as follows [12]:

$$N_{0} = \frac{2}{\pi} \arctan \left( \frac{xyz}{\sqrt{x^{2} + y^{2} + z^{2}}} \right) + \frac{1}{2\pi xyz} (F_{2} + F_{3})$$

$$+ \frac{1}{8\pi xyz} (F_{1} (x, y, z) + F_{2} (y, x, z) - F_{3} (z, x, y))$$  \hspace{1cm} (2)

where

$$F_{3} = x^{3} + y^{3} - 2z^{3} + (x^{2} + y^{2} - 2z^{2}) \sqrt{x^{2} + y^{2} + z^{2}}$$

$$F_{2} = (2z^{2} - x^{2}) \sqrt{x^{2} + y^{2} - (2z^{2} - y^{2}) \sqrt{y^{2} + z^{2}}}$$

$$- (x^{2} + y^{2})^{3/2}$$

$$F_{1} (u, v, w) = u^{2} v \log \left( \frac{u^{2} + w^{2}}{u^{2} + v^{2} + w^{2} + 2uv \sqrt{u^{2} + v^{2} + w^{2}}} \right).$$  \hspace{1cm} (3)

For the observed sample $\chi = 0.26$, $N_{0} = 0.29$. Comparison with FEA-based calculation data provided in [13] for $\chi = 0.26$ demonstrates (0.29 – 0.2899) × 100% = 0.03% of inaccuracy. Thus, the usage of (2) – (5) for the calculation of $N_{0}$ is acceptable for practical purposes.

The measured and actual $BH$- and respective $JH$-curves of the ferrite sample are depicted in Fig. 4. The intrinsic polarization curve of the PM has a clearly steeper slope than in case of the VSM open circuit measurement system. Thus, neglecting the effect of the demagnetizing field $H_d$ during VSM results’ treatment will result in incorrect determination of material’s intrinsic properties.

A demagnetizing field is present inside a PM when it is placed in a magnetic circuit of an electrical machine because of the presence of an airgap and slot openings. This field is taken into account with FEA-based program that is used in the paper for the calculation of the magnetic field strength inside the PM region during the PMSM operation.

### C. History Dependent Hysteresis Model (HDHM)

The variation of the magnetic field strength in each elementary volume of a PM in a PMSM under operation is not symmetrical with respect to the $H$-axis of its $BH$-plane and depends on the magnetic circuit configuration of the PMSM, local teeth saturation, permeance, and inverter caused harmonics. This makes the measurements of symmetrical hysteresis loops similar to that in Fig. 2, and [1] insufficient for the determination of the hysteresis loss with acceptable accuracy during actual PMSM normal operational mode.

The modeling of PMs in FEA software for electrical machine design has been provided in different ways balancing between simplicity and accuracy of models. The linearized models [14], [15] can be a good option in case of combined thermal and magnetic analysis but they neglect the hysteresis loss, in principle. The Preisach-type models are able to simulate the hysteresis behavior of a PM but are known for some considerable drawbacks, such as congruency problem, complex procedure of the model identification method, and sensitivity to measurement errors [16] – [18]. For example, the classical Preisach model (C-PM) used for the FEA simulation of NdFeB magnets in a PMSM [17] exhibit vertical congruency of minor loops, which can be absent in real magnetic materials and, therefore, can lead to an overestimation of hysteresis loss [16]. An FEM-based software using vector potential $A$ requires magnetic field strength $H$ as function of flux density $B$ or $J$ whereas C-PM output is $B(H)$ or $H(J)$. Extensive research has been carried out to overcome or at least to suppress the aforementioned drawbacks of the Preisach modeling concept [16]. As an alternative to the Preisach-type models, the phenomenological HDHM was proposed in [18] for the simulation of quasi-static $H(B)$ curves of electrical steels. The mathematics of the HDHM is able to reproduce exactly a measured main loop and incorporates the most relevant Madelung’s empirical rules, i.e., return point memory (RPM) and wiping out property [18]. The HDHM does not suffer from a congruence problem and the direct generation of $H(B)$ or $H(J)$ dependencies without any model modifications makes it attractive for implementation in transient simulators [19]– [21].

The parameters of the HDHM are defined based on the assumption that an adjustment of the model to agree with the measured major loop and a set of first-order recoil curves (FORCs), i.e., curves that start from the main loop and end at its tip, enables the simulation of high-order recoil curves with acceptable accuracy. Similar approach was followed to identify the
parameters of some Preisach-type models [17], [22] and physics-based analytical general positive-feedback (G-PFB) model [16], [23] for the simulation of semihard and hard magnetic materials. In particular, the G-PFB model demonstrated fair accuracy between model-simulated and measured reversal curves for materials with coercivities of 1.35 × 10^6 – 18 A/m, including ferrite magnet grade [24]. The hysteresis loss can change the shape of the main loop as shown in Fig. 1. The ability of the G-PFB model to reproduce exactly the measured main loop is severely limited in the mathematics employed. This can significantly degrade the model’s accuracy close to the J-axis of an initially fully polarized PM, and that is the region of interest in the study. Therefore, it is expected that the HDHM will be a reasonable compromise between implementation complexity, dataset needed for model’s identification and accuracy compared with the Preisach-type and G-PFB models in this very case.

The key assumption in the HDHM is that in the absence of accommodation (reptation) phenomenon the reversal curves of a material obey the RPM effect, i.e., any reversal curve from current arbitrary reversal point always returns to the previous reversal point. The comprehensive literature review provided in [23] demonstrates the physical and theoretical evidence that the RPM effect is normally the expected feature of hysteresis in PM materials. Fig. 5 depicts arbitrary measured recoil loops of the studied sample at ambient temperature. The reversal curve tends to travel close to the main loop after any recoil loop is formed. Such a behavior to some extent demonstrates both the RPM effect and the wiping out memory property of hysteresis used in the mathematics of the HDHM. However, detailed investigation of the measurement results in Fig. 5 reveals the presence of the accommodation phenomenon since the reversal curve does not match the main loop exactly but moves in parallel with it after the recoil loop was formed [25]. The phenomenon observed can limit the accuracy of the models incorporating the RPM effect, e.g., the HDHM used in this study, some Preisach-type models, linearized, and G-PFB models. Nevertheless, the measured loops near the J-axis in Figs. 2 and 5 show that the effect of accommodation is negligible when the magnet operates close to its fully polarized state. Similar behavior of the recoil loops were demonstrated for electrical steels [26], [27] and NdFeB magnet [6]. Some of the results in [6] (see Fig. 6 in [6]), however, are heavily corrupted by eddy currents in the tested material caused by measurement system used. As the consequence of the findings in [6], [26], and [27], and the data in Figs. 2 and 5, the accommodation phenomenon is neglected in the model used in this study. However, the effect of accommodation can be integrated into the HDHM concept as it was demonstrated in [27] with the early version of the HDHM.

The principle of the HDHM is shown in Fig. 6. For example, if for some reason the external field at point P, that lies at curve B-K-P-N in Fig. 6, is reversed and goes negative then the reversal curve P-D-B ends at the previous reversal point B. This illustrates the RPM effect described earlier. The construction of the ascending FORC B-K-P-N and the descending second-order reversal curve (SORC) P-D-B are depicted in Fig. 6 in order to clarify the mathematics used by the HDHM. The construction of any reversal curve is based on its outer loop—the loop that envelopes the reversal curve. For any FORC the outer loop matches with the main loop. The modeling principle can be applied for any order reversal curve, so the term outer loop...
Similarly to the original model [18] the choice of parameter identification procedure. Fig. 7 shows the influence model with experimentally obtained FORCs during the model’s of the hatched zone in Fig. 6 and are obtained by fitting of the always be inside its outer loop. Fig. 7 depicts the possibility in the provided ranges guaranties that any reversal curve will never existed. Similarly, if an ascending reversal curve D-S-P of nonphysical behavior of the model if coefficient d is chosen inappropriately. This can be avoided with careful balancing of all coefficients during the fitting of the model with experimental FORCs. It is seen in Fig. 5 that the shape of the FORCs depends on their starting point at the main loop. Thus, the coefficients a, b, and d are characterized by a dimensionless ratio \( \beta \) that is determined for any ascending reversal curve as follows:

\[
\beta = \frac{J_b - J_{BC}}{\Delta J}
\]

(11)

where \( \Delta J \) is the peak-to-peak polarization value of a current outer loop.

When the FORC B-K-P-N in Fig. 6 is constructed, it forms a new outer loop that is used for further computations. Now the ascending and descending branches of the outer loop are formed by B-K-P-N and N-B, respectively. The construction of the SORC P-D-B is performed in a similar way with some corrections of (6)–(11). The value of the field strength corresponding to the polarization value at an arbitrary point D that belongs to P-D-B is obtained as follows:

\[
H_D (J_D) = H_{max} (J_D) + \Delta H (J_D)
\]

(12)

The term \( \Delta H(J) \) is also determined by (8). However, the following coefficients have to be used instead of (9)–(11) for any descending reversal curve:

\[
\xi (J_D) = \frac{J_D - J_b}{J_{BC} - J_b}
\]

(13)

\[
\Delta J_{rev} = J_{BC} - J_l
\]

(14)

\[
\beta = \frac{J_{BC} - J_l}{\Delta J}
\]

(15)

where \( J_{BC} \) and \( J_l \) are the polarization values of the reversal point and the lowest point, respectively, of the current outer loop. In the observed example of P-D-B construction \( J_{BC} = J_p \), \( J_l = J_0 \), and \( \Delta J = J_N - J_0 \). The new outer loop B-K-P-D-B is formed. This loop can be used further if some arbitrary point D of the curve P-D-B will become the newest reversal point. According to the wiping out property, if the reversal curve P-D-B propagates further than B, it will continue to propagate along the descending branch of the previous outer loop, i.e., along the main loop in the observed case, as if the loop B-K-P-D-B had never existed. Similarly, if an ascending reversal curve D-S-P...
Fig. 8 shows the coefficients used in the model. Similarly to the major loops, the coefficients can be inserted in the model by using interpolation tools that are available in most commercial software.

Fig. 9 and 10 depict the comparison of measurement data (blue solid lines) and HDHM results (red dashed lines) in regions that are actually used during the PMSM operation.

Fig. 11 illustrates the comparison of the experimentally obtained hysteresis loops (blue solid lines) with the model results (red solid lines). The accuracy of (8) accounting the modeling of FORCs, and Fig. 11 depicts the comparison of the model-calculated results with some hysteresis loops in Fig. 2 corrected by (1)–(5). The slope of the major loop is not changing when it is crossing the J-axis. Such a behavior of the major loop is different from what was observed in the case of NdFeB and SmCo PMs [1]. The absence of a strong hysteretic behavior of the ferrite sample makes it possible to use the presented HDHM for the hysteresis loss evaluation in the PM material.

### III. RESULTS

A TCW RSM PMSM that was originally presented in [9] is observed in this paper. The PMSM has an external rotor topology with radially magnetized ferrite PMs. The parameters of the PMSM are provided in Table I and a sketch of the machine is depicted in Fig. 12. The topology of the observed PMSM has several advantages: short end-turns in TCW PMSMs reduce the amount of copper material needed and the application of the external rotor design allows using more magnetic material with the same overall dimensions of the machine. The main drawbacks of the TCW configuration are increased rotor core and PM losses because of significant amount of space harmonics, especially in case of high-speed machines [28]. Rotor core losses can be

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power $P$, [W]</td>
<td>90 000</td>
</tr>
<tr>
<td>Rated torque $T$, [Nm]</td>
<td>159</td>
</tr>
<tr>
<td>Rated stator current $I_s$, [A]</td>
<td>83.8</td>
</tr>
<tr>
<td>Rated spiral $a_s$, [rpm]</td>
<td>3000</td>
</tr>
<tr>
<td>Relative width of magnet on a machine’s pole $\alpha_p$</td>
<td>0.95</td>
</tr>
<tr>
<td>Permanent magnet remanence $B_r$, [T]</td>
<td>0.34</td>
</tr>
<tr>
<td>Relative permeability of the permanent magnet $\mu_r$</td>
<td>1.26</td>
</tr>
<tr>
<td>Number of stator slots $Q_s$</td>
<td>24</td>
</tr>
<tr>
<td>Number of pole pairs $p$</td>
<td>10</td>
</tr>
<tr>
<td>Permanent magnet height $h_{PM}$, [m]</td>
<td>0.017</td>
</tr>
<tr>
<td>Permanent magnet length $l_{PM}$, [m]</td>
<td>0.102</td>
</tr>
<tr>
<td>Stator outer radius $r_s$, [m]</td>
<td>0.169</td>
</tr>
<tr>
<td>Rotor inner radius $r_r$, [m]</td>
<td>0.187</td>
</tr>
<tr>
<td>Width of slot opening $b_s$, [m]</td>
<td>0.0075</td>
</tr>
<tr>
<td>Converter frequency [Hz]</td>
<td>500</td>
</tr>
<tr>
<td>Number of series turns per one coil</td>
<td>10</td>
</tr>
</tbody>
</table>
minimized by keeping a low flux density in the core during the design process. The high resistivity of ferrite PMs significantly reduces the eddy-current loss \[29\]. However, the usage of ferrite PMs can also result in a variation of the magnetic field strength between the second and the first quadrant of the BH-curve in some parts of PM as a result of strong armature reaction. This is because the relatively low PM’s remanence requires using a high linear current density to provide torque/power density at the same level as in machines with NdFeB/SmCo PMs.

This study uses commercially available FEA software Flux 2D by CEDRA T for the simulation of the observed PMSM during the normal operation. The linearized models for the magnet utilized in the software chosen neglect the variation of polarization that can occur at the linear part of main loop as depicted in Fig. 11. Thus, the usage of the magnetic field strength values provide less error for the hysteresis loss calculation with the procedure applied. The magnetic field strength values can be easily transferred to the correct flux density values for the HDHM since the structure of the model ensures that the behavior of a reversal curve starting from any arbitrary reversal point is known in advance until the next reversal point takes place \[18\].

The FEA simulations were performed with step $10^{-5}$ s for a full mechanical period of the PMSM (0.02 s) for two cases: supplying the motor with ideal sinusoidal current with rated rms value from Table I and the experimentally measured current waveform depicted in Fig. 13. The full mechanical period is chosen as the optimal time period to be used in the calculations as a compromise between the speed and the accuracy of the FEA-simulation. In such a case every elemental volume of the PMSM’s magnetic pole experiences all possible air-gap space harmonics created by the drive system. The PM was divided in $k = 11 \times 200 = 2200$ elementary volumes as shown in Fig. 12. The magnetic field strength values were calculated in each elementary volume of the PM and used then as input for the HDHM. The hysteresis loss in the whole volume of the PMSM’s pole magnet for one mechanical period $E_{hyst}$ (Joule per 0.02 s in the studied case) is calculated as the average of the calculated losses in each $i$th elemental volume of the PM $P_{hyst,i}$ multiplied by the volume of the PM as follows:

$$ E_{hyst} = \frac{1}{2p \cdot k} \sum_{i=1}^{k} P_{hyst,i} $$

whose parameters can be found in Table I. The total hysteresis loss in the whole PM material of the machine per second depends on its number of poles $2p$ and the machine’s rated speed $n$:

$$ P_{hyst} = \frac{n \cdot p \cdot E_{hyst}}{30} $$

The distribution of the loss in the volume of the PM is depicted in Fig. 14. The total losses calculated by (16) and (17) in the magnets of the observed PMSM are only 4.1 and 4.2 W for sinusoidal and frequency converter supply, respectively.

**IV. DISCUSSION**

The FEA calculated values of the field strength variation used in the calculation of the hysteresis loss in the PMSM under frequency converter supply are depicted in Fig. 15 for time period 0.001 s that is chosen as appropriate to demonstrate the main phenomena affecting the hysteresis loss. The variation of the field strength is the highest in the part of PM that is closest to the airgap and decreases considerably when approaching the rotor yoke. It is seen in Fig. 15 that the slotting creates the dominant effect on the magnetic field strength variation. The inverter caused current harmonics produce small fluctuations of the field
The variation of the field strength in the PM is additionally enhanced by the armature field spatial harmonics caused by the current fundamental, the tooth tip leakage flux effect and local tooth saturation. The phenomena have the highest influence in the parts of the PM that are closest to the airgap. Figs. 10, 11, and 15 show that the variation of the magnetic field strength of the observed machine is located on the part of the BH-curve that is traditionally considered a part with constant polarization value and linear behavior of the BH-curve, i.e., no irreversible demagnetization takes place under the field variation. The measurement results, however, show that the ferrite PM material forms minor loops that contain very little energy density. Fig. 11 shows that the magnitude of the magnetic field strength variation is the most dominant factor that affects the value of the hysteresis loss at the parts of the BH-curve that are actually used during the PMSM normal operation.

The loss distribution depicted in Fig. 14 is analyzed with the magnetic field variation in Fig. 15. The loss distribution reveals the highest losses at the air-gap surface of the PM. The highest losses are caused by the highest magnitudes of the magnetic field strength variation that take place in the part of the PM that is closest to the airgap due to the combined effect of the armature and PM fields modulated by the permeance harmonics and tooth tip leakage flux. The armature-reaction-field and permeance-variation-caused harmonics are significantly reduced when approaching from the airgap towards the rotor yoke as it can be seen in Fig. 15(a)–(c) [30], [31]. The local tooth saturation phenomenon produces additional field variation at the top of PM and, thus, increases the hysteresis loss. Fig. 15 demonstrates that the effect of tooth saturation has its highest influence at the top of PM and become negligible when approaching the rotor yoke. The hysteresis loss in other parts of the PM is significantly less compared to the air-gap surface of the PM that are closest to the airgap. The reason for that is the significantly reduced slotting effect, decreased armature field caused spatial harmonics and negligible tooth tip leakage flux effect deeper in the magnet [30], [31].

The provided measurements reveal the absence of high hysteresis losses when ferrite PM material is placed in the operating conditions of an actual PMSM including the effects of operating temperature. The hysteresis losses are calculated with the model and are equal to 0.0082% and 0.0084% of the machine nominal power [9] for pure sinusoidal and frequency converter supply, respectively. Such results clearly show that the hysteresis loss can be neglected during the design process in case of fully polarized ferrite magnets. This should be actual, also for high-speed machines, if the operational point of the PM is designed on the linear part of the BH-demagnetizing curve.

Inverter caused current harmonics can significantly increase the eddy currents in rare-earth PM material and even lead to its partial demagnetization if an electrical machine does not have very efficient cooling [32]. The model calculation results for the ferrite PM hysteresis loss show that small magnetic field strength fluctuations created by the inverter current harmonics

![Fig. 15. Field strength variation in the PM within the time period of 0.001 s under frequency converter supply. (a) Top of PM (close to airgap). (b) Middle of PM. (c) Bottom of PM (close to rotor yoke).](image)
cause only very small share of the total hysteresis loss in ferrite PMs in case of TCW PMSM topology.

V. Conclusion

The hysteresis loss was studied in a ferrite PM by means of VSM measurements, FEA simulation, and analytical model for the real operating conditions of an electrical machine. In this case, the ferrite PM did not demonstrate similar hysteresis behavior in contrary to NdFeB and SmCo PMs. Some hysteresis loss is present in the ferrite material. However, it can be neglected in most practical cases even if the PMSM is under frequency converter supply. Slotting effect together with phenomena of tooth tip leakage flux, local tooth saturation, and armature reaction space harmonics caused by the current fundamental has the dominant contribution to the magnetic field strength variation in a TCW PMSM and, thus, produce the largest part of the total hysteresis loss, whereas the influence of phase current harmonics is insignificant.

VSM is able to provide an accurate data for the analysis of PM allowing continuously and slow enough to vary the magnetic field at a fixed temperature; however, it requires the correction of measured results with demagnetizing field to get the intrinsic properties of the material that are of the most interest for the machine designer. The analytical model, which is used, has a relatively simple implementation algorithm and parameter identification procedure. It can be potentially implemented in an FEA software for electrical machine design resulting in a complementary possible option for simulation of ferrite PMs.

References


Dmitry Egorov received the B.Sc. degree from the Moscow Power Engineering Institute, Moscow, Russia, in 2013, and the M.Sc. degree in electrical engineering from the Lappeenranta University of Technology (LUT), Lappeenranta, Finland, in 2015. He is currently working toward the Doctoral degree in the Department of Electrical Engineering, LUT.

His research interests include electrical machines and drives, in particular, the applications with the permanent magnets.

Ilya Petrov received the D.Sc. degree from Lappeenranta University of Technology (LUT), Lappeenranta, Finland in 2015.

He is currently a Fellow Researcher in the Department of Electrical Engineering, LUT.

Joosep Link received the Master’s degree in engineering physics from Tallinn University of Technology (TUT), Tallinn, Estonia, in 2016. He is currently a Fellow Researcher in the Department of Electrical Engineering, Tallinn, Estonia.

His research interests include permanent magnets, multiferrics, and memristive materials.

Reivo Stern (M’16) received the M. Sc. Degree in condensed matter physics from Tartu University, Tartu, Estonia, and the Ph. D. degree in solid state physics from Zurich University, Zurich, Switzerland, in 1987, and 1995, respectively.

He is currently a Research Professor in the Department of Chemical Physics, National Institute of Chemical Physics and Biophysics, Tallinn, Estonia. His research interests include the field of various modern materials, especially quantum magnets, strong permanent magnets, and unconventional superconductors.

Juha J. Pyrhönen (M’06) born in Kuusankoski, Finland, in 1957. He received the D.Sc. degree from Lappeenranta University of Technology (LUT), Lappeenranta, Finland in 1991.

He became Professor of electrical machines and drives in LUT in 1997. He is engaged in research and development of electric motors and power-electronic-controlled drives. He has wide experience in the research and development of special electric drives for distributed power production, traction, and high-speed applications. Permanent magnet materials and applying them in machines have an important role in his research. He is currently researching new carbon-based materials for electrical machines.
Publication IV

Egorov, D., Petrov, I., Pyrhönen, J. J., Link, J., and Stern, R.
Hysteresis loss in ferrite permanent magnets in rotating electrical machinery

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Hysteresis Loss in Ferrite Permanent Magnets in Rotating Electrical Machinery

Dmitry Egorov, Ilya Petrov, Juha Pyrhonen, Senior Member, IEEE, Joosep Link, and Raivo Stern, Member, IEEE

Abstract—In this paper, hysteresis loss in magnetic poles of electrical machines with ferrite permanent magnets is studied. A vibrating sample magnetometer is used to observe the hysteresis behavior of three distinct commercial ferrite magnet grades. The measurement results indicate the presence of additional magnetic phases with reduced coercivity in the samples under study. These phases can act as an additional source of loss in ferrite magnets. A new modeling concept is introduced to simulate the hysteresis behavior of the ferrite magnet grades in the second and first quadrants of the intrinsic BH plane. Finite-element-calculated magnetic field distribution is used as an input for the analytical model to determine the hysteresis loss in the magnets of two distinct permanent magnet machine designs. The results indicate that some hysteresis loss in the ferrite permanent magnet magnetic poles of electrical machines may occur, but it plays a minor role in practice.

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

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>First coefficient in (16) determining the behavior of the constructed reversal curves.</td>
</tr>
<tr>
<td>asc</td>
<td>Spline determining the ascending branch of the respective main ( H ) curve.</td>
</tr>
<tr>
<td>( c_1 )</td>
<td>Fitting parameter determining the maximum height of the main ( H ) curve of the “soft” magnetic phase in (7) and (8).</td>
</tr>
<tr>
<td>( B )</td>
<td>Magnetic flux density [T].</td>
</tr>
<tr>
<td>( B_r )</td>
<td>Remanent magnetic flux density [T].</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>Fitting parameter determining the slope change of the main ( H ) curve of the “soft” magnetic phase in (7) and (8).</td>
</tr>
<tr>
<td>( h_s )</td>
<td>Ratio of slot opening to tooth tip width.</td>
</tr>
<tr>
<td>( f )</td>
<td>Electrical frequency [Hz].</td>
</tr>
<tr>
<td>( H )</td>
<td>Magnetic field strength [A/m].</td>
</tr>
<tr>
<td>( H_{\text{hyst}} )</td>
<td>Hysteresis loss in the magnetic pole of the machine [W].</td>
</tr>
<tr>
<td>( H_1 )</td>
<td>Lower value of magnetic field strength used in (6) [A/m].</td>
</tr>
<tr>
<td>( H_2 )</td>
<td>Higher value of magnetic field strength used in (6) [A/m].</td>
</tr>
<tr>
<td>( J )</td>
<td>Current density [A/m²].</td>
</tr>
<tr>
<td>( J_{\text{hyst}} )</td>
<td>Permeance coefficient determining the intrinsic coercivity of the ascending branch of the main ( H ) curve [T].</td>
</tr>
<tr>
<td>( J_{\text{hyst}} )</td>
<td>Spline describing the descending branch of the respective main ( H ) curve.</td>
</tr>
<tr>
<td>( J_{\text{hyst}, \text{asc}} )</td>
<td>Spline determining the ascending branch of the respective main ( H ) curve.</td>
</tr>
<tr>
<td>( J_{\text{hyst}, \text{desc}} )</td>
<td>Spline describing the descending branch of the respective main ( H ) curve.</td>
</tr>
<tr>
<td>( M )</td>
<td>Magnetization [A/m].</td>
</tr>
<tr>
<td>( N )</td>
<td>Number of turns in series turns in the stator phase.</td>
</tr>
<tr>
<td>( N_{\text{m}} )</td>
<td>Magnetometric demagnetizing factor.</td>
</tr>
<tr>
<td>( n )</td>
<td>Order of the respective reversal curve.</td>
</tr>
<tr>
<td>( P_{\text{hyst}} )</td>
<td>Calculated hysteresis energy in the ( i )-elemental volume of the magnetic pole [J/m³].</td>
</tr>
</tbody>
</table>

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D. Egorov, I. Petrov, and J. Pyrhonen are with the Department of Electrical Engineering, LUT Energy, School of Technology, Lappeenranta University of Technology, Lappeenranta, Finland (e-mail: dmitry.egorov@lut.fi; ilya.petrov@lut.fi; juha.pyrhonen@lut.fi).
J. Link and R. Stern are with the Department of Chemical Physics, National Institute of Chemical Physics and Biophysics, 12618 Tallinn, Estonia (e-mail: joosep.link@gmail.com; raivo.stern@gmail.com).
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Number of pole pairs.

Number of slots per stator.

Rotor internal radius [m].

Stator external radius [m].

Stator internal radius [m].

Surface-to-volume ratio of a magnet sample [m\(^{-1}\)].

Measured area of recoil loop [J/m\(^3\)].

Model-simulated area of recoil loop [J/m\(^3\)].

Period when the magnetic field values at each magnet point are repeated \( t_\nu \).

Volume of one magnetic pole [m\(^3\)].

Half-width of a parallelepiped sample along the \( \Delta r \)-axis [m].

Half-height of a parallelepiped sample along the \( \Delta z \)-axis [m].

Relative width of a magnet on a pole of the machine.

Relation between the height of the constructed reversal curve and the height of the current outer loop along the \( \Delta J \)-axis.

Air-gap length [m].

Parameter in (6) to smooth the descending branch of the main \( JH \) curve of the “hard” magnetic phase.

Vacuum permeability \( 4\pi \times 10^{-7} \) [H/m].

Relative permeability (of permanent magnet).

Parameter to determine the descending branch of the main \( JH \) curve of the “hard” magnetic phase [T].

Distance along the \( A \)-axis between a point on the constructed reversal curve and a point with the same polarization coordinate belonging to the current outer loop [A/m].

Distance along the \( H \)-axis between the constructed reversal curve and a point with the same polar-ization coordinate of the recoil point [A/m].

Distance along the \( J \)-axis between the current point of the constructed reversal curve and the tip of the current outer loop where the reversal curve ends [T].

Distance along the \( J \)-axis between the reversal point of the constructed reversal curve and the tip of the current outer loop where the reversal curve ends [T].

I. INTRODUCTION

PERMANENT magnet synchronous motors (PMSMs) with rare-earth (RE)-based magnets offer the highest efficiency and power/torque density solutions compared with other motor designs of similar power and speed. Nevertheless, the high cost, price volatility, unsuitable production process, and possible supply chain threats of RE materials used in permanent magnet (PM) production have boosted intensive research aiming at finding alternatives to RE PMs in electrical machinery [1]–[3]. Ferrite PM-based electrical machine designs are a viable option to overcome the RE-related mass production problems in some cases [1], [4]. The much weaker magnetic properties of ferrite magnets compared with RE PMs (e.g., SmCo and NdFeB) require special design efforts for ferrite PM machines to achieve performances comparable with the level of RE magnet machine designs [4]. The growing number of applications of electrical machines with ferrite magnets clearly reflects the increasing interest in this type of PM material [1], [4]–[6].

Any material used in the magnetic circuit of an electrical machine is usually investigated for losses that may be generated during a specific operating mode. The present-day electrical machine design relies predominantly on the finite-element method (FEM), which enables a detailed analysis of a prototyped machine. Present-day calculations of PM losses in commercial FEM software follow the eddy current loss theory [7]–[9] and the hysteresis models that consider a magnet as a material consisting of a uniform hard magnetic phase [10]–[12]. However, the latest studies clearly show the possibility of some initially fully polarized PM materials to be the source of an additional hysteresis loss, the magnitude of which can even be at the level of the eddy current loss in the worst cases [13]–[15]. Even though sufficient conditions for the hysteresis loss in PMs have been demonstrated for both RE and ferrite PM-based electrical machines, for instance, in [16], this loss is mostly neglected in the analysis.

The hysteresis loss was determined from the total magnetic ac losses in Nd-based PM by a two-frequency method and applied to the analysis of a rotor-surface-magnet PMSM in [13]. The experimental procedure in [13] estimates the losses of a magnetically short-circuited sample. This situation is not valid for PM machines, which have an air gap. Therefore, the method in [13] is prone to overestimate the PM hysteresis loss in actual PMSMs. Three commercially available PM grades (NdFeB, SmCo, and ferrite) were studied with respect to hysteresis loss at ambient temperature in [16] using a high accuracy vibrating sample magnetometer (VSM) measurement system. The measured data were used further for the calculation of the hysteresis loss in the magnetic poles of some PMSM designs. Nevertheless, inappropriate treatment of the VSM output in [16] caused a shift of the measured hysteresis loops of the samples in the second quadrant of the \( JH \) plane, and the calculated hysteresis loss was overestimated in the magnets of the machine designs under study. Furthermore, the ferrite PM sample in [16] was partially demagnetized before the measurement test, which is not a normal situation in the actual usage of PM material in electrical machinery and may lead to an increased PM hysteresis loss [12], [14]. Moreover, both the postprocessing methods used in [13] and [16] neglect the contribution of small field fluctuations, caused for instance by local saturation or tooth tip leakage flux, to the total PM hysteresis loss. Detailed VSM-based investigations of the hysteresis behavior were conducted in [17] for ferrite PM samples (BM9 grade) at the temperature of 83 °C and applied to the analysis of a tooth coil winding PMSM [17], including the effect of frequency converter current harmonics. The hysteresis loss in the PM poles of the electrical machine in [17] was determined by the combination of FEM-calculated magnetic field strength values and the history-dependent hysteresis model (HDHM). The results in [17] show that the total PM hysteresis loss can be neglected in ferrite PM motors in practice. However, the
investigations in [17] are limited to the ferrite PM grade under study.

The results available in the literature indicate that the total magnetic losses in PM materials used in electrical machinery cannot be understood with the eddy current theory and hysteresis loss in the main magnetic phase of the magnet only because of the possibility of extra hysteresis loss; however, this loss is usually neglected in the conventional efficiency analysis of PM machines. The magnitude of PM hysteresis loss in PM poles is still unclear both for RE- and ferrite-based PM machine designs. This paper studies the hysteresis loss phenomenon in the ferrite PM magnetic poles of PMSMs. The hysteresis behavior of three commercially available ferrite PM grades is investigated by a high accuracy VSM-based measurement system. A combination of FEM-based calculations and a newly introduced analytical modeling concept is used to determine the total hysteresis loss in the magnetic poles of a tooth coil winding PMSM with an external flux PMSM design with an open slot structure [18].

This paper is organized as follows. Section II presents the details of the measurement tests and the analytical model principle. Calculated results taking into account the hysteresis loss in PMs of the studied PMSM topologies are presented in Section III. Discussion of the results is provided in Section IV. Section V concludes the paper.

II. METHODS

A. Measurement Equipment and Procedure

A physical-properties-measurement system with up to 14 Tesla superconducting magnets developed by Quantum Design with a P255 VSM option and a data acquisition system is used in the study. The VSM-based measurement system contains the continuous and slow enough variation of the magnetic field acting on the sample. The open magnetic circuit of the VSM eliminates the distortion of the measured results caused by the extra hysteresis loss and eddy currents that may occur in the yokes of the devices with a closed magnetic circuit, for instance, the hysteresis graph and installations used in [13] and [14]. The drawback of the VSM is the demagnetizing field in the sample having an air gap in its magnetic circuit. The output of the VSM, that is, the polarization current that has not directly correspond to the intrinsic properties of the material, which are represented as J with respect to the internal field H. The postprocessing of the VSM data requires correction of each measured point (J, H) as follows [19]:

\[ H_{\text{corr}} = H_L - \frac{N_{\text{m}}}{\mu_0} J \]  

(1)

where \( N_{\text{m}} \) is the magnetometric demagnetizing factor and \( \mu_0 = 4\pi \times 10^{-7} \) [H/m] is vacuum permeability. Assuming that the relative permeability of the ferrite PM \( \mu_r \) is close to one [19], [20], \( N_{\text{m}} \) can be determined analytically for a parallelepiped-shape sample with the dimensions \( 2x \times 2y \times 2z(M^3) \) and the magnetization \( M \) along the z-axis as follows [21]:

\[ N_{\mu} = \frac{2}{\pi} \arctan \left( \frac{xy}{\sqrt{x^2 + y^2 + z^2}} \right) + \frac{1}{3\pi xyz} (F_2 + F_3) \]

\[ + \frac{1}{2\pi xyz} \left( F_{11}(x, y, z) + F_{11}(y, x, z) - F_{11}(z, x, y) - F_{11}(z, y, x) \right) \]

(2)

where

\[ F_2 = x^4 + y^4 - 2z^4 + \left( x^2 + y^2 - 2z^2 \right) \sqrt{x^2 + y^2 + z^2} \]

\[ F_3 = \left( 2z^2 - x^2 \right)^{1/2} \sqrt{x^2 + y^2 + z^2} \]

\[ F_{11}(u, v, w) = u^2 v \log \frac{u^2 + v^2}{u^2 + 2v^2 + w^2 + u^2 + 2v^2 + 2w^2 + 2u^2 + v^2 + w^2} \]

(4)

The FEM-calculated values of \( N_{\mu} \) [22] show a close match to the analytically calculated values in the case of PMs, and therefore, the use of (2)–(5) is applicable for practical purposes when magnets of a parallelepiped shape are measured.

Fig. 1 depicts the three samples of different ferrite PM grades used in the study. The sample of each grade was randomly selected from a batch ordered from a manufacturer. Based on the information provided by the manufacturer, the magnets to be studied were produced by a hydrothermal synthesis method. The temperature of the measurements was selected to be 80°C, which corresponds to the normal operating temperatures of ferrite PM machines [4], [6]. The samples were fixed in the VSM sample holder with glass and nonmagnetic glue.

The measurement procedure comprised of three separate tests for each sample. In the first test, the main \( JH \) curve and sets of first-order reversal curves (FORCs) were measured. The starting points of the FORCs were selected within an interval from an initially fully polarized state to the normal coercivity \( H_{\text{c0}} \) of the respective sample. This region corresponds to the second and first quadrants of the BH plane of the magnet, which are of the highest interest for a convenient loss analysis of magnetic components in rotating electrical machinery [23]. The second test included observation of the sample behavior within the second quadrant of the intrinsic \( JH \) plane. The details of the measurement sequence can be found in [12]. In the third test, several arbitrary reversal curves up to the fourth order
were measured when the applied magnetic field strength was strong enough to move the operating point of the magnet from the second quadrant of the intrinsic \( JH \) plane to the first and back. Fig. 2 depicts the main \( JH \) curves of the samples together with some measurement results according to the test procedures described in the paper.

The unusual behavior of the measured curves is clearly observable for all the samples. The main \( JH \) curves show a considerable change in the slope at the external magnetic field strength values around \(-120 \text{ kA/m}\) when passing through the second quadrant of the \( JH \) plane of the initially fully polarized PM. The FORCs starting from magnetic field strength values lower than \(-120 \text{ kA/m}\) also exhibit an unexpected behavior when reaching magnetic field strength values around 40–80 \( \text{kA/m} \) for all the tested samples. The results of the second test for the Y32H-2 grade show no wide loops when the internal magnetic field strength is varied in the second quadrant of the \( JH \) plane. However, the data of the third test for the Y28H-2 grade reveal that considerable loops can occur if the magnetic field strength is strong enough to move the operating point of the PM from the second quadrant to the first quadrant and back. The possibility of the magnetic field strength in PMs to vary between the second and first quadrants of the intrinsic \( JH \) plane has been reported for rotor-surface-magnet PMSMs with a tooth coil winding [17] and a distributed winding in [13] and [16], for traction motors [15] in their normal operating modes. Therefore, the hysteresis loops of the PMs depicted in Fig. 2 can result in additional losses in the PMs of PMSMs, yet these losses are neglected in the present-day analysis of PM electrical machines.

**B. Origin of Hysteresis Loss**

The VSM output indicates the average response of all magnetic phases in the sample volume to the highly homogeneous applied field. The sample may have structural defects that can be located in the sample volume or generated at the surface during the machining (or cutting) of the magnet. Ferrite magnets produced by the hydrothermal synthesis method can have unwanted phases of iron oxide \( \alpha-Fe_2O_3 \) [24] and orthorhombic barium iron oxide \( \text{BaFe}_2\text{O}_4 \) [25] as impurities in addition to the major phase of the hexagonal barium M-type ferrite \( \text{BaFe}_{12}\text{O}_{19} \). The coercivities of both these undesirable phases at ambient temperature can be in the range of the anomaly in Fig. 2 [26]–[28], which supports the assumption about the volumetric origin of the hysteresis loss in ferrite PMs.

The studies of Nd-based magnets mostly assume that the hysteresis loss originates from the reduced coercivity of the damaged grains on the sample surface [14], [29]. The results in [29] show that the heat treatment of a thin NdFeB PM sample with the surface-to-volume ratio \( S/V = 21.9 \text{ mm}^{-3} \) in temperatures exceeding the melting point of the Nd-rich phase results in a considerable reduction in the unexpected slope change near the \( J \)-axis, but does not fully eliminate it. The \( JH \) curve of the sample in [29] still indicates an unexpected decrease in polarization at magnetic field strength values below the intrinsic coercivity [\( H_{Ji} \)]. The NdFeB sample with a relatively small \( S/V = 1.82 \text{ mm}^{-3} (3.1 \times 2.9 \times 4.1 (\text{mm})^3) \) in [16] demonstrates a considerable slope change near the \( J \)-axis while the ferrite sample of the BM9 grade in [17] with \( S/V = 1.72 \text{ mm}^{-3} (3 \times 3.6 \times 4 (\text{mm})^3) \) does not exhibit a similar behavior of the recoil curves. The pulse field magnetometer measurement results in [30] show the possibility of hysteresis loss in Nd- and SmCo-based PM samples even with values of \( S/V = 0.4–0.6 \text{ mm}^{-3} \). The recent research [31] provides convincing evidence that the hysteresis loss can partly be an intrinsic property of the Nd-based magnet material, generated in the PM manufacturing as a negative consequence of enhanced coercivity.

Based on the observations available about the possible origin of the hysteresis loss in PMs, it was concluded that both volume- and surface-caused defects can be present in ferrite PMs simultaneously. Thin RE PMs used in electrical machinery obviously contain a considerable proportion of damaged grains on the magnet surface. This damage is caused by the machining phase in the production process if no other surface treatment is applied. However, the relatively weak magnetic properties of the ferrite PMs facilitate the designs of PMSMs with thick magnets to avoid possible irreversible demagnetization of ferrite magnet material [4]. Therefore, the hysteresis loss in ferrite magnets with dimensions relevant to the actual machine design will mostly be associated with volumetric defects. This study assumes that the behavior of the recoil curves in Fig. 2 is caused by the presence of unwanted magnetic phases, which are equally distributed in the PM volume.

**C. Modeling of Hysteresis Loss**

The measured hysteresis behavior of the samples in Fig. 2 is caused by a combination of multiple phases with markedly different magnetic properties compared with the main phase properties. Most of the hysteresis models have been developed for materials consisting of one magnetic phase, and thus,
require modification to the case under study. Some concepts based on closed-form operators, such as Preisach, Stop, and Play models, make an exception. They, however, may suffer from certain drawbacks such as the congruency problem, sensitivity to measurement errors, a complex procedure of parameter identification, which can be highly computer intensive, and the inverse problem [32]–[38]. These drawbacks have partly been resolved in various studies, but simulation of a material consisting of multiple phases requires a lot of measurement data for model identification, and unpredictable errors are still possible [36].

The modeling concept introduced in this study is based on the coexistence of multiple magnetic phases in the PM volume. The hysteresis behavior of the recoil loops in Fig. 2 is suggested to be represented as a combination of artificial “hard” and “soft” magnetic phases acting simultaneously (the “soft” phase is actually hard in nature, but it is called soft because of the presence of the main phase with much harder magnetic properties). The artificial phases are assumed not to show an unnatural hysteresis behavior of reversal curves similar to that observed in Fig. 2, in other words, they consist predominantly of one magnetic phase. Therefore, the measured behavior of the samples can be simulated by a combination of two hysteresis models representing “hard” and “soft” artificial phases. This study uses two HDHMs [33] to simulate the measured hysteresis behavior of the samples illustrated in Fig. 2. The advantages of the HDHM modeling concept include the absence of congruency of the recoil curves, a straightforward parameter identification algorithm, and an ability to reproduce the major loop of any shape owing to the splines used. The spline technique also enables the HDHM to have \( H \) or \( B(J) \) data as the model input. The mathematics of the HDHM incorporates the most relevant empirical rules of hysteresis observed by Madelung, in other words, in the absence of the reptation phenomenon, the reversal curves of the material obey the return point memory effect and the wipping out property rule [33]. The HDHM principle assumes that fitting of the model-simulated results with the measured main loop and the sets of FORCs enables simulation of other reversal curves with a sufficient accuracy. Similar empirical rules and parameter identification procedures are implemented in other models, for instance, in some Preisach-type models [10], [37], physics-based general-positive feedback theory [32], [36], and the behavioral magneto-static modeling approach [38]. Recent measurement results demonstrate that a reptation (accommodation) phenomenon is actually present in real PMs [12], [15], [17]; however, it has a negligible effect on the hysteresis behavior of recoil curves when a PM operates close to its fully polarized state, that is, in the region of interest in this study [17], [23], [32]. The modeling concepts [32], [34]–[38] can also be used as an alternative to the HDHM in the case under study. However, some of the mathematical instruments of the models [32], [34]–[38] offer a relatively limited option to adjust the measured and simulated main loop and the set of FORCs with the HDHM. This can lead to a higher error of the model-simulated results by default. The output of the HDHM can be \( H(J) \) or \( B(J) \) values, which promotes the use of the model in transient simulators [33], [39]–[42]. This feature may be absent in the Preisach and the Play model [34], [43].

The mathematical structure and parameter identification procedure of the HDHM makes it possible to simulate part of the \( JH \) curve of a material, which considerably reduces the amount of measurement data required. In the case under study, the HDHM approach is applied according to the following new procedure with the Y28H-2 grade PM sample as example.

**Step 1: Creation of the major loops for artificial “hard” and “soft” magnetic phases.**

The simulation region is limited by the part of the main \( JH \) loop \( \text{desc}(H) \) and the FORC \( \text{asc}(H) \) starting from the value of the magnetic field strength close to \( H_{ab} \) as depicted in Fig. 3. The descending main curve of the “hard” magnetic phase \( \text{desc}_{\text{hard}}(H) \) is generated by the summation of \( \text{desc}(H) \) with the parameter \( \Delta R \), which provides the acceptable smoothness of the resulting curve

\[
\Delta B = \begin{cases} 
\text{desc}(H) - \text{desc}_{\text{hard}}(H) & H < H_1 \\
\text{desc}(H) - \text{desc}_{\text{hard}}(H) & H > H_2 
\end{cases}
\]

where the values of \( H_1, H_2 \), and \( \zeta \) are determined manually and the data in \( \text{desc}_{\text{hard}}(H) \) in the range of \( H_1 < H < H_2 \) are wiped out. The correct adjustment of the \( H_1, H_2 \), and \( \zeta \) results in a descending main loop of the artificial “soft” phase \( \text{desc}_{\text{soft}}(H) = \text{desc}(H) - \text{desc}_{\text{hard}}(H) \), which will not experience a nonphysical behavior \( dB/dH < 0 \) and can be described as follows:

\[
\text{desc}_{\text{soft}}(H) = n_1 \tanh (b_1 \times (H + c_1))
\]

where \( a_1, b_1, \) and \( c_1 \) are fitting parameters. After \( a_1, b_1, \) and \( c_1 \) have been defined, the ascending main loop for the artificially “soft” magnetic phase \( \text{asc}_{\text{soft}}(H) \) is determined as follows:

\[
\text{asc}_{\text{soft}}(H) = a_2 \tanh (b_2 \times (H + c_2))
\]

where \( c_2 \) is selected in a way that eliminates, as much as possible, the steep slope change of the ascending main curve of the
artificial hard magnetic phase. The values of $H_1$, $H_2$, $\zeta$, $b_1$, $c_1$, and $c_2$ in (6)–(8) for the samples are presented in Table I.

Step 2: Simultaneous parameter identification of HDHM for artificial “soft” and “hard” magnetic phases.

The details of HDHM are exhaustively explained in [33] with an example of ferrite PM modeling in [17], and therefore, they are discussed only in brief in this paper. The HDHM concept uses the gap $\Delta H(J)$ that determines the distance between the constructed reversal curve and the current outer loop. The outer loop is the loop that envelopes the constructed curve, and it is always known in advance from the previous magnetization history. In general, the reversal curve of the nth order is constructed by using the $n–2$ and $n–1$ previous reversal curves (the main loop of the material is considered a zero-order reversal curve). This paper introduces a modified expression for $\Delta H(J)$ from [17] with a reduced number of parameters needed for the model identification:

$$\Delta H(J) = \Delta H_{\text{asc}}(J_{\text{asc}}) \cdot (1 - d) \frac{\Delta J(J)}{\Delta J_{\text{rev}}} + d \cdot (H_{\text{asc}}(J) - H_{\text{asc}}(J_{\text{asc}}))$$

where $J_{\text{asc}}$ is the polarization coordinate of the reversal point, $H_{\text{asc}}(J)$ and $H_{\text{asc}}(J_{\text{asc}})$ represent the ascending and descending branches of the current outer loop, and $\Delta H_{\text{asc}}(J_{\text{asc}}) = H_{\text{asc}}(J_{\text{asc}}) - H_{\text{asc}}(J_{\text{asc}})$. The values of $\Delta R(J)$ and $\Delta J_{\text{ash}}$ are determined as shown in Fig. 4 with a third ORC $n = 3$ as an example. The behavior of the reversal curve depends on its starting point at the current outer loop, and is described by a set of coefficients $a(\beta) > 0$, $0 \geq b(\beta) \geq 1$. The values of $a(\beta)$ and $b(\beta)$ are determined by fitting the model-simulated results with the measured sets of FORCs in the parameter identification procedure of the model. The parameter $\beta$ is defined as follows:

$$\beta = \frac{\Delta J_{\text{ash}}}{\Delta J_{\text{ash}}}$$

where $\Delta J_{\text{ash}}$ is the height of the current outer loop. The use of (8) instead of the original expression in [17] simplifies the procedure of the model identification yet maintaining an adequate accuracy of the model-simulated results in the region under study. The coefficients $a(\beta)$ and $b(\beta)$ are determined simultaneously to get the sum of FORCs of two artificial phases corresponding to the resulting measured FORCs. Fig. 5 depicts the coefficients for three grades obtained in the fitting procedure. Fig. 6 shows a comparison of the simulated and measured results.
III. RESULTS

Fig. 7 presents the model-simulated areas of recoil loops \([J/m^3]\) for the Y32H-2 grade at the selected measurement temperature when the internal field strength is varied between \(H_{\text{min}}\) and \(H_{\text{max}}\) values of an initially fully polarized sample. The results in Fig. 7 follow the idea of measurements provided in [13] and [14], but allow getting an extended representation of possible values of the hysteresis loss at the linear part of the main BH curve. A comparison with experimental data from the second and third measurement tests is provided where available. The model-simulated and measured areas of the recoil loops \(S_{\text{mod}}\) and \(S_{\text{meas}}\) are compared by a relative inaccuracy method \((S_{\text{meas}} - S_{\text{mod}}) \times 100\% / S_{\text{meas}}\).

Rotor-surface-magnet PMSM designs have the highest risk for the hysteresis loss because the air gap magnetic field harmonics penetrate directly into the magnets without being damped in the rotor steel as, for example, in the PMSMs with embedded magnetic poles [16], [23], [44]. The tooth coil winding configuration offers significant manufacturing advantages such as a simple winding process and short end windings. The drawback of the tooth coil winding arrangement is the higher number of magnetic field harmonics compared with distributed winding machine designs. Variation of the magnetic field in the magnetic poles of the machine is also increased by the slotting effect, which is typically more severe in tooth coil winding than in distributed winding designs of similar power and speed [45]. Therefore, ferrite rotor-surface-magnet tooth coil winding PMSM with an external rotor topology [4], [45] and double stator tooth coil winding axial flux PMSM [18] designs are chosen in this study. The rotor-surface-magnet tooth coil winding PMSM was investigated for the PM loss in [17], and the hysteresis losses were calculated to be negligible in practice. The measured data of the BM9 PM grade in [17] do not show significant hysteresis loops similar to those observed in Figs. 2 and 6 for the grades under study. Therefore, the value of the hysteresis loss is of interest when the original BM9 grade in [17] is replaced by the PM grades investigated in this paper.

The initial design of the 100 kW 1500 r/min axial flux PMSM with NdFeB PMs in [18] showed about 15 kW of PM loss (with nonsegmented magnets) caused by the eddy current phenomenon. The high variation of the magnetic field in the PM poles is due to the combined effect of the open slot stator structure together with the armature reaction spatial harmonics produced by the phase current fundamental. The PMs of the axial flux PMSM in [18] were segmented and covered by steel laminations to reduce the influence of undesired field harmonics travelling through the magnetic poles. The high electrical resistivity of ferrite PMs allows to neglect the eddy current loss phenomenon in ferrite magnets in the electrical machine design [45]. Therefore, the focus of analysis is usually on the PM...
demagnetization when investigating the PM material in a ferrite magnetic machine [4]. Thus, the final design of the axial flux PM in [18] was modified for this study: the NdFeB magnets were replaced by ferrite magnets with the same dimensions, the iron covers at the PM surface were removed, and the magnitude of the phase current was reduced to avoid partial demagnetization of the machine poles in the normal operating mode. The parameters and sketches of the machines are given in Table II and Fig. 8, respectively. The magnetic properties of the studied PM samples are approximated by the linear model with two parameters (remanence $B_r$, relative permeability $\mu_r$), and they are used for the two-dimensional simulation of the observed electrical machine designs with the commercially available software FLUX by Altair/CEDRA T. The linear modeling concept takes into account the change in the PM polarization as follows:

$$ J_\text{PM-pole} (H_i) = B_r + (\mu_r - 1) \cdot H_i (11) $$

which is a reasonable compromise between the implementation complexity of the model, computation cost, and accuracy in the case of the chosen procedure of the hysteresis loss calculation [17]. The PM poles of the electrical machines were divided into 11 layers with 200 points at each layer, that is, $k = 11 \times 200 = 2200$ elemental volumes. The magnetic field strength values in each volume were determined under sinusoidal supply at the time $t_{\nu}$, corresponding to the period when each point of the PM has been exposed to all possible values of the field in the specific operating mode. The value of $t_{\nu}$ in the case under study depends on the electrical frequency $f$, the number of pole pairs $p$, and the number of slots per stator $Q_s$ of the machine

$$ t_{\nu} = \frac{1}{f} \cdot \frac{2p}{Q_s} (12) $$

The FEM results for the magnetic field strength in each volume were used as the input for the HDHMs, and the hysteresis loss in the machine was calculated as follows:

$$ E_{\text{hyst}} = 2 \cdot p \cdot V_{\text{PM-pole}} \cdot \sum_{i=1}^{k} P_{\text{hyst},i} (13) $$

where $V_{\text{PM-pole}}$ is the volume of one PM pole, and $P_{\text{hyst},i}$ is the model-calculated loss in the $i$-elemental volume of the PM for the time period $t_{\nu}$. Figs. 9 and 10 show the distribution of the hysteresis loss and the maximum/minimum values of the magnetic field strength in the magnetic poles of the machine designs. The parameters used for the linear PM model in the FEM software are defined from the data in Fig. 2: $B_r = 0.334 \text{T}$, $\mu_r = 1.094$ for the Y28H-2 grade, $B_r = 0.349 \text{T}$, $\mu_r = 1.101$ for the Y32H-2 grade, and $B_r = 0.358 \text{T}$, $\mu_r = 1.099$ for the C8 grade. The values of the calculated hysteresis loss for all PM material in the magnetic poles of the investigated tooth coil winding PMSM topology with an external rotor are 28.37 (0.056% of the machine output power $P_{\text{out}}$), 21.73 (0.041% $P_{\text{out}}$), and 24.24 W (0.045% $P_{\text{out}}$) for the Y28H-2, Y32H-2, and C8 PM grades, respectively. The calculated values of the hysteresis loss for the double stator tooth coil winding axial flux PMSM design are 14.2 (0.32% $P_{\text{out}}$), 11.5 (0.25% $P_{\text{out}}$),

Table II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rotor-surface magnet PMSM</th>
<th>Axial flux PMSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-gap length $d$ [m]</td>
<td>0.001</td>
<td>0.0015</td>
</tr>
<tr>
<td>Electrical frequency $f$ [Hz]</td>
<td>500</td>
<td>125</td>
</tr>
<tr>
<td>Machine length in the axial direction $l$ [m]</td>
<td>0.102</td>
<td>0.167</td>
</tr>
<tr>
<td>Number of pole pairs $p$</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Number of series turns per phase per stator $N$</td>
<td>40</td>
<td>64</td>
</tr>
<tr>
<td>Number of slots per stator $Q_s$</td>
<td>24</td>
<td>42</td>
</tr>
<tr>
<td>Period when magnetic field values at each magnet point are repeated $t_{\nu}$</td>
<td>0.0017</td>
<td>0.0067</td>
</tr>
</tbody>
</table>

Fig. 8. Two-dimensional FEA sketches of the studied PMSMs. (a) Tooth coil winding rotor-surface-magnet PMSM. (b) Tooth coil winding axial flux PMSM.

Fig. 9. Model-calculated hysteresis loss and FEM-simulated magnetic field strength variation (Y28H-2 grade). The machine rotates counterclockwise in the motoring mode. (a) Hysteresis loss distribution in the pole of the tooth coil winding PMSM with an external rotor topology. (b) Minimum and maximum values of the magnetic field strength in the normal operating mode at the surface (close to the air gap, solid line), middle (cross-dashed line), and bottom (close to the rotor hub, circle-dotted line) in the PM pole.
design procedure to enable PM poles to withstand short-circuit magnetic field variation is practically avoided in the machine and 11.8 W (0.25% of the PM.

Some small hysteresis losses are possible if the results are consistent with the data of test 3 in Figs. 2 and 6. A hysteresis loss distribution at the surface (close to the air gap, solid line), 2/11 of the magnetic field strength variation at the surface (cross-dashed line), and middle (circle-dotted line) of the PM.

Fig. 10. Model-calculated hysteresis loss and FEM-simulated magnetic field strength variation (Y28H-2 grade). The machine rotates counterclockwise in the motoring mode. (a) Hysteresis loss distribution in the pole of the double stator axial flux PMSM. (b) Minimum and maximum values of the magnetic field strength in the PM pole in the normal operating mode at the surface (close to the air gap, solid line), 2/11 of the magnetic field strength from the surface (cross-dashed line), and middle (circle-dotted line) of the PM.

and 11.8 W (0.25% of the PM) for the Y28H-2, Y32H-2, and C8 PM grades, respectively.

IV. DISCUSSION

The model-simulated losses in Fig. 7 are negligible when the PM operates at the second quadrant of the BH plane. These results are consistent with the data of test 3 in Figs. 2 and 6. Some small hysteresis losses are possible if the magnetic field strength variation at the surface of the PM pole is a result of the highest proportion of the hysteresis loss is concentrated on the surface-magnet PMSM with an external rotor topology. The limited height of the PM pole close to the air gap makes it possible to use bulk poles in the machine, and they are expected not to produce any loss. A rotor construction combining fiber glass and ferrite magnets allows, in principle, manufacturing a rotor with negligible amount of magnetic-field-caused losses.

However, the results in Figs. 7 and 10 show the possibility of unexpected loss in the PM material resulting from the presence of magnetic phases with reduced coercivity. The studied samples showed an unexpected hysteresis behavior compared with other parts of the magnetic pole. The high coercivity of RE PMs compared with ferrite magnets enables a higher armature reaction field, which can result in increased variation of the magnetic field strength in the magnetic pole of the machine. The height of the RE PM pole could be in the range of a couple of millimeters, and in other words, all the volume of the RE magnet material in the electrical machine can be exposed to a considerable variation of the magnetic field as it can be seen in Figs. 9 and 10. The results found in the literature [14], [29] provide convincing evidence that the cutting of the magnet can create phases with reduced coercivity at the sample surface. These phases can significantly increase the total hysteresis loss of RE magnets. Thus, the RE PM poles of electrical machines in some designs are expected to have markedly higher hysteresis losses, which are often missed in the present-day loss analysis of electrical machines.

V. CONCLUSION

In this paper, three commercial ferrite PM grades were measured by the VSM in the region of the BH curve corresponding to the normal operation of PM material in electrical machinery. The studied samples showed an unexpected hysteresis behavior caused by the presence of magnetic phases with markedly softer magnetic properties compared with the expected hard magnetic phase of hexagonal barium M-type ferrite. Unwanted magnetic
phases in ferrite PMs can originate both from impurities in the raw materials and surface damages induced in the final magnet machining stage; however, in ferrite magnets with dimensions relevant to the actual machine design, the former phenomenon is expected to be more significant than the latter. Magnetic phases with reduced coercivity can result in additional loss in ferrite PMs.

The hysteresis behavior of the initially fully polarized samples in the first quadrant and in the linear part of the second quadrant of the BH plane was modeled by the combination of two HDHMs. The applied modeling concept is able to simulate the hysteresis behavior of a PM within a desired region of the main HI curve only, which significantly reduces the amount of measurement data required for the parameter identification of the model. The proposed simulation method can be further improved to be applicable to studies of the hysteresis loss phenomenon in RE PMs used in rotating electrical machinery.

The hysteresis loss in the magnetic poles of two ferrite PM machine designs under sinusoidal supply was determined by the combination of the FEM-calculated magnetic field distribution in the PM regions of the machines and the proposed modeling concept. The calculation results indicate that the actual hysteresis loss in ferrite PM poles of the studied PMSMs is small in practice. However, in some cases, it can be a source of considerable additional loss in the ferrite magnet material. The currently available commercial FEM software tools for electrical machine design usually ignore the contribution of the observed hysteresis loss phenomenon to the total loss in the PM material. The amount of hysteresis loss in the magnetic poles of RE PM-based motors has still not been assessed properly and remains to be studied.

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Dmitry Egorov received the B.Sc. degree in electrical engineering from Moscow Power En-
gineering Institute, Moscow, Russia, in 2013, and the M.Sc. degree in electrical engineering from
the Lappeenranta University of Technology (LUT), Lappeenranta, Finland, in 2015. He is currently working toward the Doctoral degree in electrical drives at the Department of Electrical Engineering, LUT.

His research interests include electrical ma-
chines and drives, in particular, the applications with the permanent magnets.

Ilya Petrov received the D.Sc. degree in electri-
cal drives from Lappeenranta University of Tech-
nology (LUT), Lappeenranta, Finland, in 2015. He is currently a Research Fellow with the
Department of Electrical Engineering, LUT.

Juha Pyrhonen (M’06–SM’17) born in 1957 in
Kuusankoski, Finland. He received the D.Sc.
degree in electrical engineering from Lappeen-
ranta University of Technology (LUT), Lappeen-
ranta, Finland, in 1991.

In 1997, he became a Professor of Electri-
cal Machines and Drives with LUT. He is en-
gaged in research and development of electric
motors and power-electronics-controlled drives.
He has wide experience in the research and
development of special electric drives for dis-
tributed power production, traction and high-speed applications. Perma-
nent magnet materials and applying them in machines have an important
role in his research. Currently, he is also researching new carbon-based
materials for electrical machines.

Joosep Link received the Master’s degree in
engineering physics from Tallinn University
of Technology (TUT), Tallinn, Estonia, in 2016. He is currently working toward the Doctoral degree in engineering physics with TUT.

He is an early-stage Researcher with the De-
partment of Chemical Physics, National Institute of Chemical Physics and Biophysics, Tallinn. His research interests include permanent magnets, multiferroics, and memristive materials.

Raivo Stern (M’16) received the M.Sc. degree in condensed matter physics from Tartu Uni-
versity, Tartu, Estonia, in 1987, and the Ph.D.
degree in solid-state physics from Zurich Uni-
versity, Zurich, Switzerland, in 1995.

He is currently a Research Professor with the
Department of Chemical Physics, National Insti-
tute of Chemical Physics and Biophysics, Tallinn, Estonia. His research interests include the field of various modern materials, especially quan-
tum magnets, strong permanent magnets, and
unconventional superconductors.
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Linear Recoil Curve Demagnetization Models for Ferrite Magnets in Rotating Machinery

Dmitry Egorov, Ilya Petrov, Juha Pyrhönen
Department of Electrical Engineering,
Lappeenranta University of Technology
Lappeenranta, Finland
dmitry.egorov@lut.fi, ilya.petrov@lut.fi,
juha.pyrhonen@lut.fi

Joosep Link, and Raivo Stern
Laboratory of Chemical Physics,
National Institute of Chemical Physics and Biophysics
Tallinn, Estonia
joosep.link@kbfi.ee, raivo.stern@kbfi.ee

Abstract—Electrical motors with ferrite Permanent Magnets (PM) are a possible solution when avoiding the usage of rare earth materials in rotating machinery. Irreversible demagnetization of the ferrite PMs is one of the key challenges that need to be analyzed in such designs. Nowadays electrical machine design is increasingly relying on Finite Element Analysis (FEA) software that require having accurate and easy-to-implement models for a magnet. Linear Recoil Curve (LRC) models are among the best candidates. This paper studies the LRC models for FEA simulation of ferrite PMs in rotating machinery. Comparison of the model-based results with high accuracy Vibrating Sample Magnetometer (VSM) measured data for a commercially available ferrite magnet grade show that none of the existing temperature dependent LRC models is universal. However, the further development of the studied modelling concept can offer an accurate tool for FEA simulation of ferrite PMs in electrical machines.

Keywords—demagnetization models; ferrite magnets; finite-element analysis; permanent magnet machines

I. INTRODUCTION

Electrical machines with Permanent Magnet (PM) excitation may offer higher efficiency and power density solutions compared with other electrical machine types of similar power and speed having electrical excitation. Rare Earth (RE) magnets have a high energy density and, therefore, are preferable in applications with limited physical space, such as electrical vehicles [1]. However, the limited availability and significant price volatility of RE metals has led to extensive research for alternative designs of electrical machines with reduced amount of RE PMs or totally without them [1], [2]. Machine’s volume is not a limiting factor, electrical machine designs with ferrite magnet material can be a viable option. Ferrite magnets demonstrate stable pricing over decades and are significantly cheaper compared to RE magnets [2]. Nowadays, ferrite PMs are widely used in designs of Permanent Magnet Synchronous Machines (PMSM) [3], [4], DC motors [5], [6], PM assisted Synchronous Reluctance (PMaSynR) [1], [2] and some switched reluctance machine types [7].

Ferrite magnets have considerably lower values of remanence $B_r$ and coercivity $H_c$ compared to typical RE PM grades (i.e. NdFeB and SmCo). The low coercivity $H_c$ of ferrite PM, and therefore its weak capability to withstand irreversible demagnetization makes it important to perform PM’s partial demagnetization analysis during the design process of a machine with ferrite magnet material [2]-[7].

The Finite Element Analysis (FEA) is a conventional tool for electrical machine design since it enables relatively simple and detailed analysis of each component’s influence on the overall machine performance. The permanent magnet material in FEA has been modelled in different ways using e.g. variable magnetization and Stoner-Wohlfarth model methods [8], [9], Preisach-type models [10], [11], non-Preisach History Dependent Hysteresis Model (HDHM) or Linear Recoil Curve (LRC) models [12]-[14].

Variable magnetization and Stoner-Wohlfarth model methods are appropriate for magnetization processes rather than simulation of permanent magnet material in an electrical machine and are limited by a possibly complex shape of PMSM’s magnetic pole [6], [9]. Classical Preisach model has been considered in [10] for the simulation of NdFeB PM in synchronous motor and it demonstrated adequate accuracy within the 2nd and 3rd quadrants of the magnet’s $BH$-plane. Nevertheless, the drawbacks of the Preisach models are relatively complicated implementation algorithm, sensitivity to measurement errors and identification method problems [15]. HDHM was used in [13] for the simulation of NdFeB PM and it demonstrated slightly optimistic back-EMF calculation results after partial demagnetization of NdFeB magnet. The implementation of HDHM provided in [13] requires using a relatively complicated transplantation method.

LRC models are widely used tools for PM’s demagnetization analysis using FEA software due to an easy implementation algorithm and a lower amount of input parameters. The parameters can be made temperature dependent and, thus, enable coupled thermal and magnetic simulation of an electrical machine [12], [13]. LRC models are considered to be appropriate for any type of PMs and demonstrate adequate accuracy for some NdFeB magnets [13], [16]. However, very little attention has been paid to the experimental verification of the ability of the LRC models to describe the macroscopic behavior of ferrite PMs despite that they are widely used in FEA softwares during design of electrical machines with ferrite magnet material [3], [7].
The operating point of a magnet during the normal operational mode of a PMSM can also cross the second and the third quadrants of the BH-curve, which are regions of interest since the BH-curve directly should be preferred. However, according to the experience of the authors the extremely accurate measurements needed in case of searching the hysteresis behavior of permanent magnet materials cannot be done with such devices as extra hysteresis and eddy currents in the magnetic yoke of the measurement device easily corrupt the measurement results. In [18] a most probably eddy-current-corrupted result of a hysteresisgraph measurement is seen. Therefore, the VSM is used even though the interpretation of the results becomes more difficult, since VSM open circuit measurement results need to be corrected for each measurement point \((J, H_i)\) as:

\[
H_{i,j} = H_{i,j} + \frac{N_{m}}{\mu_0} J_i ,
\]

where \(N_{m}\) is a magnetometric demagnetizing factor, \(\mu_0 = 4\pi \times 10^{-7} \text{ H/m}\) is the permeability of vacuum and the demagnetizing field is assumed to be proportional to the polarization [21].

Assuming that the magnetic susceptibility \(\chi\) of the ferrite magnet is close to zero \(N_{m}\) can be calculated analytically for a parallelepiped shape sample with the dimensions \(2a \times 2b \times 2c\) as follows [22]:

\[
N_{m} = \frac{2}{\pi} \arctan \left( \frac{ab}{\sqrt{a^2 + b^2 + c^2}} \right) + \frac{1}{3\pi abc} \left( F_2 + F_3 \right) + \frac{1}{2\pi abc} \left( F_4 (a,b,c) + F_5 (b,a,c) - F_6 (c,a,b) - F_7 (c,b,a) \right) ,
\]

where

\[
F_2 = a^2 + b^2 - 2c^2 - \sqrt{a^2 + b^2 - 2c^2} \sqrt{a^2 + b^2 + c^2} ,
\]

\[
F_3 = 2c^2 - a^2 \sqrt{a^2 + b^2 + c^2} + c^2 - \left( a^2 + b^2 + c^2 \right)^{3/2} ,
\]

\[
F_4 (a,b,c) = a^2 \log \left( a^2 + w^2 \right) \left( a^2 + 2w^2 + 2\sqrt{a^2 + w^2} \right) ,
\]

\[
F_5 (b,a,c) = b^2 \log \left( b^2 + 2w^2 + w^2 + 2\sqrt{b^2 + w^2} \right) ,
\]

\[
F_6 (c,a,b) = c^2 \log \left( c^2 + 2w^2 + w^2 + 2\sqrt{c^2 + w^2} \right) ,
\]

\[
F_7 (c,b,a) = c^2 \log \left( c^2 + 2w^2 + w^2 + 2\sqrt{c^2 + w^2} \right) ,
\]

The measurement procedure included two separate tests at the chosen temperature. During the first test, the main BH-loop and the First Order Reversal Curves (FORCs) were measured. FORCs are the curves that start at some point of the main BH-
loop and end at the fully polarized state of the magnet. During the second test, recoil loops of the ferrite magnet in the 2nd and 3rd quadrants of the intrinsic JH-plane were obtained by implementing an additional script in the VSM’s software. The script’s principle is shown in Fig. 2. The results of the VSM measurements are depicted in Fig. 3 along with intrinsic curves of the observed sample. The intrinsic curves were found by applying (1)-(5) to the VSM measured results.

Fig. 2 demonstrates that the intrinsic JH-curve of the material has a clearly steeper slope than the output of the VSM. Thus, neglecting the use of (1)-(5), i.e. building the model based on the VSM output, would result in a misunderstanding of the actual magnetic properties of the material. The comparison of the measured main JH-loop delivered by the first test with the data from the second test in Fig. 3(b) demonstrate the processes of reversible demagnetization experienced by each recoil loop. The JH-curve from the second test does not exactly match with the main JH-loop but moves somewhat parallel to it after the recoil loops were formed. This can be explained by the presence of the accommodation (reptation) effect in the observed material that leads to a difference in the magnet’s hysteresis behavior depending on its previous demagnetization history [23]. The results obtained with analogous measurement procedure for five different hard magnetic materials in [24] show that with an acceptable margin of error the accommodation effect can be neglected in the case studied. Therefore, the J(H) data in Fig. 3(b) are converted to B(H) as [21]:

\[ B_i = J_i + \mu_0 H_i \]

and are treated in the way that every recoil loop is assumed to exhibit a perfect return point memory feature, i.e. its starting point matches with the ending point.

B. LRC models

LRC models use straight lines to model the recoil loops of a magnet both for fully magnetized and partially demagnetized cases. These models are the coercivity limit model, the linear vertical [25] and the linear sloped [14] models or exponential [13] and hyperbolic tangent function [12] models. The coercivity limit and the linear vertical models were excluded from this study due to limited ability to simulate post demagnetization performances of PM compared with other models [13], [14].

Despite different possible implementation algorithms, the general principle of the studied LRC models in FEA is the same and is depicted in Fig. 4. Actual PM flux density is described as a line whose slope and value at zero field strength are determined by the recoil permeability \( \mu_{\text{rec}} \) and remanence \( B_r \), respectively. The demagnetization BH-curve of the magnet (blue line in Fig. 4) has a linear region that corresponds to the magnetic field strength values from fully polarized state of the PM in the 1st quadrant up to point \( (H_{\text{in}}, B_{\text{in}}) \) where the knee region starts. In the linear region of the BH-curve the polarization value is assumed to be a constant where no irreversible processes of the PM’s demagnetization take place. At the field values below \( H_{\text{in}} \) the magnet starts to lose its polarization irreversibly and, therefore, its magnetic properties need to be updated. It is seen in Fig. 4 that the new \( B^{\text{new}}(H) \) in case of partial PM demagnetization can be found from the current worst operating point of the PM \( P(B_{\text{in}}, H_{\text{in}}) \) as [26]:

\[ B_i = J_i + \mu_0 H_i \]
where \( \mu_{\text{rec}} \) is determined from the linear part of the PM’s demagnetization curve [13]. The obtained \( B_{\text{new}}(H) \) will be valid until the operating point goes further negative. If a stronger than \( H_p \) negative magnetic field strength is achieved then \( B(H) \) is recalculated again by (7) according to the new worst operating point. The recoil permeability can be determined for any recoil loop as [21]:

\[
\mu_{\text{rec}} = \frac{\Delta B}{\mu_0 \Delta H}
\]

where \( \Delta B \) and \( \Delta H \) characterize the mean slope of a given recoil loop as shown in Fig. 4.

The difference between the studied models is in the mathematical tools used for the modelling of the PM’s demagnetization \( BH \)-curve. One of the ways that can be used for the linear sloped model is the following:

\[
B^{\text{new}}(H) = (B_p - \mu_0 \mu_{\text{rec}} H_p) + \mu_0 \mu_{\text{rec}} H ,
\]

where \( \mu_{\text{rec}} \) is determined from the linear part of the PM’s demagnetization curve [13]. The obtained \( B^{\text{new}}(H) \) will be valid until the operating point goes further negative. If a stronger than \( H_p \) negative magnetic field strength is achieved then \( B(H) \) is recalculated again by (7) according to the new worst operating point. The recoil permeability can be determined for any recoil loop as [21]:

\[
\mu_{\text{rec}} = \frac{\Delta B}{\mu_0 \Delta H}
\]

where \( \Delta B \) and \( \Delta H \) characterize the mean slope of a given recoil loop as shown in Fig. 4.

The analysis of Figs. (4)-(6) shows that the accuracy of the models under consideration depends on \( \mu_{\text{rec}} \) and the mathematical means used for the description of the PM’s demagnetization curve. The influence of the assumption about
the constant value of $\mu_{rec}$ and (9)-(12) to the predictive ability of the LRC models is investigated in the following section.

III. RESULTS AND ANALYSIS

In order to verify the predictive ability of the considered LRC models and the general accuracy of such a modelling concept in case of ferrite magnets further two additional models with the same principle were included into the study: 1) a spline model with constant permeability where the demagnetization curve exactly matches with the measured one and the value of $\mu_{rec}$ used in (7) is constant, being the object of optimization, and 2) a spline model with non-constant permeability that also uses the exact main BH-curve. However, the value of $\mu_{rec}$ in (7) is dependent on the maximum negative intrinsic magnetic field experienced by the magnet. The values of $\mu_{rec}$ used in the model were determined from the data in Fig. 3(a) and are depicted in Fig. 6. For a fair comparison, the linear sloped, the exponential and the hyperbolic tangent function models were fitted with the measured BH-curve at the magnetic field strength values within $(0, H_c)$ as the magnetic properties of PMs are typically provided by manufacturers in this range [21], [27]. Table I depicts the parameters of the models determined by optimization techniques. The linear sloped and exponential models include $\mu_{rec}$ in (9)-(11) as coefficient determined during the fitting while the value of $\mu_{rec}$ in the hyperbolic tangent function model (12) is always equal to one [12], [13]. For all the models $B_t = 0.355 \ T$ and $H_{Jd} = -322 \ kA/m$ were used if applicable.

Fig. 7 depicts the differences between the measured and the demagnetization curves modelled by (9)-(12) with the parameters of Table I. The comparison of results in Fig. 7 for the linear sloped and exponential models show that in the cases studied the latter demonstrates a better ability to fit the experimentally measured demagnetization curve at the magnetic field strength values $(H_{Jd}, 0)$. This is controversial to the results provided in [16] for NdFeB magnet where the linear slope model has the best fitting. Fig. 7 shows that both the linear sloped and exponential models cannot be used to model the demagnetization curve at the magnetic field strength values below $H_{Jd}$ as the difference between measured and model-based demagnetization curves become too large. The mathematical means (12) used by the hyperbolic tangent function model demonstrate a better fitting to the experimental demagnetization curve compared with (9)-(11) for almost all negative magnetic field strength values as it can be seen in Fig. 7. The relatively close matching of the modelled and the measured demagnetization curves is the good prerequisite but not a guarantee of the model’s accuracy as it can contribute to the model’s possible error. Therefore, the data in Fig. 5 are used further to investigate the accuracy of the LRC models studied here.

Normalized Root Mean Square Deviation (NRMSD) was used in [28] to compare the accuracy of some models for electrical steel hysteresis and is chosen to be used also in this paper as an adequate quantitative tool to assess the predictive ability of the observed LRC models. The NRMSD is determined for every recoil loop in Fig. 5 as:

$$ \text{NRMSD} = \frac{1}{B_{max} - B_{min}} \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{B_{meas, i} - B_{calc, i}}{B_{meas, i}} \right)^2} \times 100\% \quad (12) $$

where $B_{max}$ and $B_{min}$ are maximum and minimum flux density values of a loop, $B_{meas, i}$ represents measured values of recoil loop, $B_{calc}$ is calculated by (7) and respective mathematical tools used by the models with the coefficients from Table I, $n$ is the number of the measured points in the recoil loop. The results calculated by (12) can be slightly different depending on machine’s magnetic circuit configuration that determines the slope of load line. For clarity, this study investigates the accuracy of the LRC models to predict the intrinsic properties.
of a material, i.e. \( H = H_a \). Fig. 8 shows the NRMSDs for the studied models accounting the examined ferrite grade.

The comparison of the linear sloped, exponential and tangent function models is performed first as they require a small amount of input parameters to become temperature dependent. Figs. (6)-(8) show that the accuracy of the hyperbolic tangent function model, at the linear region of demagnetization curve caused by the better fitting, reduces considerably when approaching the knee region as the result of the actual \( \mu_{\text{rec}} \) is increasing. All the three models have close values of residuals at the beginning of the knee region, however, the value of \( \mu_{\text{rec}} \) used by the hyperbolic tangent model leads to a worse prediction ability compared to the linear sloped and the exponential models. The accuracy of the hyperbolic tangent function model is better when moving further to the negative magnetic field strength values. This is caused by a better fitting to the demagnetization curve and decreasing value of \( \mu_{\text{rec}} \) as it can be observed from Figs. (6)-(7). The difference in the prediction ability of the linear sloped and exponential model in the case studied is caused mainly by fitting to experimental demagnetization curve as it can be seen in Figs. (7)-(8) and in the values of \( \mu_{\text{rec}} \) in Table I. The data in Figs. (7)-(8) indicate that the sharpness of the knee region can cause significant errors in the output of the model as the flux density of the magnet can change dramatically within a relatively small range of magnetic field strength. The comparison of the total accuracy of the models depicted in Fig. 8 shows that the linear sloped and exponential models should be preferable if the magnet operates close to the knee region and if there is a risk of partial PM’s demagnetization in normal operational mode of a machine. It can be missed by some PM demagnetization models. The hyperbolic tangent model will be more reliable to analyze the performances of the machine after severe faults, e.g. short circuit.

Fig. 9 depicts a comparison of the measured recoil loops with the results from spline-based models defined with parameters from Table I. The data in Fig. 9 clearly show that the LRC model with the experimentally measured demagnetization curve could have adequate accuracy accounting PM’s hysteretic behavior within the 2nd and the 3rd quadrant of the \( BH \)-plane if the magnet is initially fully polarized. The NRMSD does not exceed 17% and 5% for the spline models with \( \mu_{\text{rec}} = \text{const} \) and \( \mu_{\text{rec}} \neq \text{const} \), respectively as it can be seen from Fig. 8.

Comparison of the spline models with the measured results demonstrates the best accuracy within the models studied. The measured recoil loops in the second and in the third quadrants are very narrow and, thus, the modelling concept used by the LRC models is accurate enough if the mathematical tools describing the demagnetization curve show a good agreement with the measured curve and the value of \( \mu_{\text{rec}} \) is selected accordingly. The observed behavior of the recoil loops in the second and the third quadrant of the \( BH \)-plane in Fig. 5 and the data in Fig. 6 show that the \( \mu_{\text{rec}}(H_{\text{start}}) \) can be determined also from the FORCs. This simplifies the measurement procedure needed for the model’s parameter identification.

IV. CONCLUSION

The concept of the LRC models for the PM simulation in electrical machinery was investigated for a commercially available ferrite magnet material. VSM-obtained open circuit measurement data were used to determine the intrinsic properties of the studied ferrite sample. The results are clearly indicating that there is no universal LRC model existing. The difference between the actual and modelled demagnetization curves leads to significant inaccuracies in the prediction of the magnet’s hysteretic behavior, especially at the knee region of a PM. The assumption about a constant \( \mu_{\text{rec}} \) is acceptable if the LRC model is able to describe the main \( BH \)-loop exactly and the value of \( \mu_{\text{rec}} \) is appropriately selected.

Linear sloped and exponential models are not appropriate for the simulation of PM’s hysteretic behavior at the magnetic field strength values below \( H_c \), nevertheless, demonstrate better accuracy compared with the hyperbolic tangent function model close to the beginning of knee region of the \( BH \)-curve. The linear sloped and exponential models can be a good tool during combined thermal and electromagnetic machine’s analysis in order to determine the possibility of partial PM’s
demagnetization but can be not accurate enough to track post-demagnetizing performances of a magnet after severe faults when the operating point can fall close to $H_D$ and further negative values.

The LRC models based on exact experimentally measured demagnetization characteristic $BH$-curve cannot simulate quite accurately the actual ferrite PM's behavior within the 2nd and the 3rd quadrants even if prior is assumed to be constant. Such models, however, are built at fixed operating temperature of the magnet and cannot be easily made temperature-dependent based on a couple of parameters. The LRC model based on measured $BH$-loop and set of FORCs offer accurate tool with simple implementation and parameter identification procedures for the simulation of a ferrite magnet's hysteretic behavior in rotating machinery.

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