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Model for Angular Dependency of the Intrinsic Coercivity of Ferrite Permanent Magnets

Marcelo D. Silva¹, Emil Lind¹, Anar Ibrayeva¹, Sagar Ghorai² and Sandra Eriksson¹
¹Department of Electrical Engineering, Uppsala University, Uppsala 752 37, Sweden
²Department of Materials Science and Engineering, Uppsala University, Uppsala 751 03, Sweden

In internal permanent magnet synchronous machines (IPMSM), the use of ferrite permanent magnets is being studied as an alternative to rare-earth elements-based permanent magnets, such as NdFeB. However, demagnetization measurements of ferrite magnets are rarely published and such information is crucial for an efficient electrical machine design with ferrite magnets. In this paper, we present measurements of partial demagnetization on ferrite permanent magnets subject to inclined external magnetic fields. From the measurements done, mathematical models are developed for Y30 and Y40 samples that defines a relationship between the intrinsic coercivity and the inclination of the external demagnetizing field. Furthermore, from the primary results, the angular dependency of hysteresis losses and relative permeability are also explored, as well as their impact on the design of IPMSM.

Index Terms—Angular Demagnetization, Ferrite Magnets, Intrinsic Coercivity, Magnetic Field Modeling.

I. INTRODUCTION

The use of ferrite permanent magnets (PM) is common in applications requiring low magnetic energy product $BH_{\text{max}}$ and low cost. In the case of applications requiring higher $BH_{\text{max}}$, rare-earth elements-based (REE) PMs are often used, such as NdFeB PM. Although, the use of REE gives rise to supply-chain, political and environmental problems [1].

Internal permanent magnet synchronous machines (IPMSM) is one of the applications requiring high $BH_{\text{max}}$, although to avoid the issue mentioned previously, ferrite PM has been studied as an alternative to NdFeB [2]. However, differences in both the magnetic intrinsic coercivity, $H_c$, and the magnetic remanence, $B_r$, creates challenges.

Ferrite PMs have, compared with NdFeB, inferior properties for magnetic intrinsic coercivity, $H_c$, which turns them more prone to permanent demagnetization due to winding faults or during field weakening operation. The mitigation of permanent demagnetization can be done by carefully designing the shape of the PM and the shape of the magnetic circuit around it.

Spoke Type IPMSM is an effective topology for use of ferrite PMs, due to its capacity to concentrate magnetic flux. Although, such topology tends to expose the PM to inclined demagnetizing fields [3]. The calculation of permanent demagnetization considering the inclination angle of the external field is then necessary to produce reliable simulations.

Previous studies on the angular dependence of the intrinsic coercive force were done for NdFeB PM in [4]. In [5] a study on the angular dependence of coercive force of ferrite magnets is presented, although the tests were conducted on ferrite powder samples, not in commercially graded samples. Additionally, proposed models of angular dependency, [6] and [7], have been shown to not produce accurate predictions of the intrinsic coercivity for different angles of the external demagnetization fields.

In this paper, the aim is to measure the permanent demagnetization of Y30 and Y40 ferrite samples for different inclinations of the external demagnetizing field. The measurements are used for the development of a mathematical model relating the inclination of the external demagnetizing field and the intrinsic coercivity of the samples. In the next section, a brief explanation of the theory is presented, followed by an explanation of the study procedure and the measurement results. In the last sections, the results and their implications for electrical machine design are discussed and the mathematical models are developed.

II. THEORY

The behaviour of the magnetic flux density generated by a PM, given an internal magnetic field can be modelled either by:

$$B = \mu_0 (\mu_r H + M_r),$$

or:

$$B = \mu_0 \mu_r H + B_r,$$

where, $B$ is the magnetic flux density, $H$ is the internal magnetic field strength, $M_r$ is the remanent magnetization and $B_r$ is the remanence. Additionally, $\mu_0$ and $\mu_r$ are the vacuum and relative magnetic permeability, respectively.

The internal magnetic field is dependent on the applied field, $H_a$, the demagnetization factor, $N$, and the magnetization of the PM, $M$. Although, laboratory measurements using vibrating samples magnetometer (VSM) can only detect the applied field. The equation describing its dependences with the other magnetic field components is:

$$H_a = H + NM,$$

From the previous equations we can concluded that the magnetic flux density has two contributions. The first is the
contribution of the applied magnetic field. The other contribution has it origins in the magnetization of the PM, described in (1) by $\mu_0 M_r$ and in (2) by $B_r$.

Therefore, the applied magnetic field can contribute to reinforce the magnetization of the sample, or to cancel it. For a certain applied field the magnetic flux density, $B$, is zero. Coercivity, $H_c$, is defined at this level of field strength. When the PM reaches its coercivity, it is also possible to observe demagnetization, although, this demagnetization is not necessarily permanent.

At the same time, the applied magnetic field also has an influence on the magnetization, $M$, of the PM sample. The magnetization of a PM also describes the orientation of the magnetic domains inside it. If the applied magnetic field is parallel to the orientation of these domains, the overall magnetic domains inside it. If, instead, an antiparallel applied magnetic field is considered, this will cause the rotation of some magnetic domains, reducing the overall magnetization of the PM sample. Eventually, the applied magnetic field, $H_a$, reaches a field strength for which the magnetization will be zero. This level of field strength is known as the intrinsic coercivity of the PM, $H_{ci}$. Usually, when the working point of a PM reaches $H_{ci}$, permanent demagnetization is observable.

A model describing the relation between the intrinsic coercivity, $H_{ci}$, and the angle of the external demagnetizing field is used in [8] and first developed by [6]. The model follows:

$$H_{ci}^\beta = H_{ci}^{\beta=0} / \cos(\beta)$$

where $\beta$ is the angle between the magnetization of the PM and the external demagnetizing field.

Another way of looking into the angular dependency of the intrinsic coercivity is through the Stoner-Wohlfarth model [7]. The non-parallelism between the magnetization direction and the external field generates an energy that is counterbalanced by the parallelism between the magnetization direction and the anisotropic axis. In each magnetic domain, these two energies balance each other. This mechanism justifies the need for stronger external demagnetizing field to reach the intrinsic coercivity when it has an angle with the magnetization direction.

Nevertheless, it has been proven in [4] and [9] that neither of these models can predict the angular dependency satisfactorily. Due to these mismatches, it is still necessary to do empirical measurements to know how the angular dependency of the intrinsic coercivity behaves.

Lastly, most of the commercial tools that calculate electromagnetic fields based on finite element methods (FEM) use a simple model that only considers the antiparallel component of the magnetic flux density, $B$.

III. EXPERIMENTAL METHOD

The analysis used ferrite PM graded as Y30 and Y40 with the shape of a prism. The dimensions of the samples are $2\ mm \times 2\ mm \times 3\ mm$, with the magnetization direction parallel to the $3\ mm$ dimension. The magnetic characterization of the samples was determined using a vibrating samples magnetometer (VSM, Lakeshore 7400) with a range of applied field of $\pm 800\ kA/m$. The measurements were done every $1.8\ kA/m$ for the major loop, and every $3.\ kA/m$ for the minor hysteresis loops. The whole characterization process was conducted at room temperature.

In order to guarantee the same state at the beginning of the demagnetization process, the samples are magnetized parallel to the easy axis until saturation is reached. The sample is then rotated to a defined angle and after that, the demagnetizing field is applied. The magnetization, $M$, of the sample, is recorded, as well as, the corresponding levels of the applied field. This process is carried on until the applied magnetic field strength amplitude is higher than the amplitude of the intrinsic coercivity.

The procedure described is repeated for $0^\circ$, $30^\circ$ and $60^\circ$ of inclination of the external demagnetizing field for Y30 samples. The samples of Y40 were submitted to the process described previously for $0^\circ$, $15^\circ$, $30^\circ$ and $45^\circ$.

IV. RESULTS

In this section we start by showing the direct measurements from the VSM, that is the $MH$ curves for Y30 and Y40 samples, followed by the angular dependency of the intrinsic coercivity on both samples. Following that step, the description is done for indirect results, possible to infer from the direct measurements. Those are the $BH$ curves, the permeability of the linear region of the $BH$ curves and the area of the minor loops of $MH$ curves from the Y30 and Y40 samples.

A. MH Curves

The $MH$ curves describing the demagnetization of the Y30 and Y40 samples for the different angles of inclination are presented in Fig. 1 and Fig. 2. These results indicate an increase of the intrinsic coercivity, $H_{ci}$, with the increase of the inclination angle, $\beta$. For both Y30 and Y40, that dependency is illustrated in 3.

![MH Curves](image)

Fig. 1. $MH$ curves of the Y30 sample at different angles of inclination of the external demagnetizing fields. Black dotted lines are a mathematical extrapolation.

From Fig. 4 and Fig. 5 it is possible to observe that the recoil lines and the area of the minor hysteresis loops increases with $\beta$ for the Y30 samples. The minor hysteresis loops of the Y40 samples are visible in Fig. 6 and Fig. 7, and those also show a similar reaction to the increase of $\beta$.  

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The permeability increases with the intrinsic coercivity, $H_{ci}$, of the Y30 and Y40 samples in the linear region. This aspect is important to analyse, as is presented in Table I. In Table II the minor hysteresis loops are numbered starting with the one with the higher absolute value of magnetization.

### B. BH Curves and Change in Relative Permeability, $\mu_r$

The direct measurements make it possible to calculate the magnetic flux density, in order to analyse the $BH$ curves. The following equation is used for the calculation:

$$ B = \mu_0(M + H_a - NM) = \mu_0(M + H), $$

where $N$ is the demagnetization factor. Due to the shape of the sample, the theoretical demagnetization factor is 0.25 [10]. Although, in practice it was needed to adapt it, $N$, to 0.2025.

Analysing the $BH$ curves of Y30 in Fig. 8 and of Y40 in Fig. 9, shows that the coercivity, $H_{c}$, has the opposite tendency of the intrinsic coercivity, $H_{ci}$. The former decreases with $\beta$. Furthermore, it is possible to detect a change in the relative permeability in both Y30 and Y40 samples in the linear region. The permeability increases with $\beta$. As is presented in Table I.

### C. Area of the Minor Hysteresis Loops of $MH$ Curves

The areas of the minor hysteresis loops of $MH$ curves for Y30 and Y40 samples are also affected by $\beta$, which can be observed in Figs. 4, 5, 6 and 7. This aspect is important to analyse because these areas are proportional to the hysteresis losses in PM. In [11] the hysteresis losses on ferrite PM were studied deeply, but there is no study on the angular dependency. In Table II and Table III, it is shown that the area of the minor hysteresis loops, expressed in units of area (u.a), is highly dependent on the inclination of the external demagnetizing field. These areas were calculated using absolute values of the $MH$ curves, and subtracting the integral of the lower part from the integral of the upper part of the minor hysteresis loops.

### D. Comparison between Results and Standard Values

The comparison of the results based on measurements for $\beta = 0$ and the standard characteristics of ferrite PM graded

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>RELATIVE PERMEABILITY VARIATION OF THE Y30 AND Y40 SAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>Y30 Permeability, $\mu_r$</td>
</tr>
<tr>
<td>0°</td>
<td>1.27</td>
</tr>
<tr>
<td>15°</td>
<td>-</td>
</tr>
<tr>
<td>30°</td>
<td>1.34</td>
</tr>
<tr>
<td>45°</td>
<td>-</td>
</tr>
<tr>
<td>60°</td>
<td>1.56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>AREA OF THE MINOR HYSTERESIS LOOPS FROM Y30 SAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>Minor Loop 1 [u.a.]</td>
</tr>
<tr>
<td>0°</td>
<td>2.26</td>
</tr>
<tr>
<td>30°</td>
<td>6.72</td>
</tr>
<tr>
<td>60°</td>
<td>29.0</td>
</tr>
</tbody>
</table>
as Y30 and Y40 is presented in Table IV. Most of the characteristics are within of the limits and the only one that is significantly outside the values is the $H_r$ for Y40 and its deviation is of 3.3%. $B_r$ here was found from extrapolation, see Fig. 8 and 9.

V. MATHEMATICAL MODEL

In [4] the relation between $H_{ci}$ and $\beta$ is established using a third-order polynomial for NdFeB PM. To establish mathematical models for Y30 and Y40, a similar technique was used. Although, the optimal fit for the Y30 measurements is done by using a second-order polynomial, such as:

$$H_{ci}(\beta) = H_{ci}^{\beta=0}(1 + a_1\beta + a_2\beta^2)$$  \hspace{1cm} (6)

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Loop 1 [u.a.]</th>
<th>Loop 2 [u.a.]</th>
<th>Loop 3 [u.a.]</th>
<th>Loop 4 [u.a.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.14</td>
<td>2.25</td>
<td>7.44</td>
<td>45.3</td>
</tr>
<tr>
<td>15°</td>
<td>0.90</td>
<td>8.67</td>
<td>44.1</td>
<td>115</td>
</tr>
<tr>
<td>30°</td>
<td>2.25</td>
<td>26.3</td>
<td>287</td>
<td>562</td>
</tr>
<tr>
<td>45°</td>
<td>3.60</td>
<td>54.6</td>
<td>296</td>
<td>777</td>
</tr>
</tbody>
</table>

TABLE IV

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Y30 Standard Results</th>
<th>Y40 Standard Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{ci}[\text{kA/m}]$</td>
<td>180 - 220</td>
<td>199</td>
</tr>
<tr>
<td>$H_r[\text{kA/m}]$</td>
<td>175 - 210</td>
<td>194</td>
</tr>
<tr>
<td>$B_r[\text{mT}]$</td>
<td>370 - 400</td>
<td>402</td>
</tr>
</tbody>
</table>

VI. IMPACT ON ELECTRICAL MACHINE DESIGN

The results shown previously and the mathematical models described in the last section indicate angular dependency of, not only, the intrinsic coercivity, $H_{ci}$, but also of relative permeability, $\mu_r$, and the hysteresis losses.

In both ferrite samples, Y30 and Y40, the presence of angular dependency of intrinsic coercivity, $H_{ci}$, is visible. Although, the mathematical model describing this dependency is distinct for the two different samples. For Y30 the dependency is almost proportional to the inclination angle, $\beta$. Such can
also be confirmed by examining the coefficients in Table V. For Y40, the intrinsic coercivity remains mostly constant until \( \beta \) reaches around 30°. After that point, the intrinsic coercivity starts to increase significantly. This behaviour was expected from previous studies, [4] [5]. Although it highlights the need to conduct empirical tests for each of the PM grades intended to use in the application being designed.

Given that most of the software solving electromagnetic fields using FEM is using the model from [6], and comparing the prediction of that model with the practical results, it is expected that most of the permanent demagnetization results from FEM models are optimistic. Such is a smaller problem for PM operating far from the intrinsic coercivity, \( H_{ci} \), since that the permanent demagnetization risk is low, as it happens with PM based on NdFeB. Although, it turns into a bigger problem when designing high-performance applications using ferrite PM because the optimisation in these pushes the PM working point near to the permanent demagnetization. In those situations having a precise description of the PM is crucial.

Table I shows the angular dependence of the relative permeability, \( \mu_r \), of the Y30 and Y40 samples. The evolution is small and the impact of this variation should be of small magnitude. Although, if the PM is being used in a highly saturated ferromagnetic magnetic circuit and under an external demagnetizing field with high \( \beta \), having the PM with higher relative permeability, \( \mu_r \), can cause some unexpected behaviour. Nevertheless, new studies and measurements are needed in order to fully understand the extent of the impact.

Contrary to what is seen for the relative permeability, the hysteresis losses can be highly impacted by the inclination angle, \( \beta \), of the external demagnetizing field. In Table II and Table III, it is clear that the minor hysteresis loop areas increase significantly with the inclination angle, \( \beta \), and so do the hysteresis losses [11]. In the case of IPMSM the working point of the PM is constantly changing. The change of the working point follows these minor loops, which are especially evident after permanent demagnetization has occurred. Therefore, a PM under highly inclined demagnetizing fields presents substantially higher hysteresis losses than a PM under parallel demagnetizing fields.

Nevertheless, it is important to put into perspective this increase. The hysteresis losses in ferrite PM are a small fraction of the total losses. Although producing a design that in some parts can multiply them up to 12.8 times, could turn them significant and cause unexpected behaviour in the machine. To quantify the impact of the angular dependence of hysteresis losses in PM it is necessary to conduct more experiments.

VII. CONCLUSION

From the results shown in this study, it is clear that the models in use do not represent the measurements of \( H_{ci}(\beta) \) for Y30 or Y40 ferrite PM samples. The adoption of such a model includes uncertainty in the simulation results. Such is problematic as the design of a competitive IPMSM with ferrite depends on defining the working point of the PM near the demagnetization threshold, i.e., near an unstable region. The use of this new model should allow the development of a more precise FEM model, allowing a more precise design of the performance of the machine.

The values for the coefficients obtained for Y30 and Y40 ferrite PM are significantly different from the coefficients obtained previously for NdFeB samples. Not only that but also the mathematical model for the ferrite PM samples of different grades are also different and use different coefficients. Such implies that universal coefficients do not exist and that different grades need to be tested individually in order to know the angular dependency of the intrinsic coercivity, \( H_{ci} \).

The results above show that ferrite PM under inclined demagnetizing field presents angular dependency not only regarding intrinsic coercivity but also for relative permeability and hysteresis losses. The last two dependencies were not quantified or mathematical modelled, although a short qualitative analysis was done. To further understand the behaviour and impact of the angular dependency of the two last PM characteristics more experiments are needed in the future.

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