Abstract—End users’ concerns about permanent magnet stability sometimes limit the growing use of sintered NdFeB magnets. In this work the magnetization losses with time are demonstrated for five different types of NdFeB materials. In addition to room temperature, four elevated holding temperatures were used. The coercivity of the material was found to have a strong effect on the stability of the magnet, but its stability is also greatly affected by the permeance coefficient of the magnet. High coercivity materials together with a high permeance coefficient give very small losses even at 150°C after an eight-thousand hour trial period.

Index Terms—NdFeB, Permanent Magnet, Stability, Magnetization Losses, Aging

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I. INTRODUCTION

The number of NdFeB magnets used in industrial motor applications has increased in recent years. These machines are designed for a lifetime of 20 to 30 years. Therefore one important design issue is the stability of the magnets.

The total flux loss in a magnet is composed of reversible loss, recoverable irreversible loss and structural loss [1]. BH-curves at different temperatures reveal the reversible losses of a magnet as the decrease in remanent magnetization. This is a phenomenon characteristic of the material.

Structural losses are due to phase changes, typically caused by oxidation in NdFeB magnets. Temperatures under the Curie point of NdFeB magnets cannot cause phase changes. Structural losses due to oxidation can be avoided with proper corrosion protection.

Recoverable irreversible losses are due to magnetization reversal phenomena and these losses are recoverable by remagnetization. Remagnetization of magnets is, however, impossible in motor applications and therefore the control of these losses is important.

Magnetization reversal may be activated by increasing the opposite magnetic field or raising the temperature. Irreversible losses due to rising field and temperature can be determined from the BH curves of a material at different temperatures. These losses are also dependent on the working point of the magnet. In static magnetic field and temperature, the magnetization reversal can be activated by the magnetic viscosity effect. Magnetic viscosity is a statistical relaxation phenomenon due to thermal fluctuation in the non-equilibrium state of the material [2].

Time dependence of the magnetization is described by logarithmic law:

\[ M(t, H) = M(t_0, H) - S(H) \ln \frac{t}{t_0} \]  

Where \( S \) is a phenomenological magnetic viscosity constant and \( t_0 \) is a reference time. Wohlfarth et. al. [3] have determined the magnetic viscosity constant as:

\[ S = \frac{kT}{\upsilon K} f(H, T)M_s \]  

Where \( kT \) represents the temperature dependency, \( \upsilon K \) (\( \upsilon \) is the activation volume, \( K \) is the anisotropy constant) depends on the material and its
The microstructure and \( f(H,T) \) is a complicated function, which describes the precise nature of the magnetization process. Thus, magnetization losses with time in permanent magnets are dependent on the magnetic field, temperature, magnet material and its microstructure and the magnetization process. In this work we studied magnetization losses with time in sintered NdFeB magnets by varying the temperature, composition and the permeance coefficient of the magnet.

### II. Method

Five different commercial NdFeB magnet compositions were tested. Coercivities and Dy content of these materials are listed in table 1. One of the samples also had an addition of cobalt.

The number of identical samples varied between 9 and 21. All samples had a rectangular shape with a cross section of 10x10mm. The heights of the samples varied according to tested permeance coefficients \( \text{Pc} = 0.33, 1.1 \) and 3.3 (h = 1.6 mm, 4.6 mm and 10.5 mm). The samples were fully magnetized in a 3.5 T pulsed field. The reference value of the flux of each sample was measured with a Helmholtz coil immediately after the magnetization. After reference measurement, the samples were kept at 5 different temperatures: room temperature (23 °C), 60°C, 80°C, 120°C and 150°C. Elevated temperatures were generated with StabiliTherm EU2 ovens with a temperature accuracy of ±0.5°C. The first measurement was carried out after an hour and the following measurements were carried out at suitable time intervals. The samples were cooled down to room temperature before each measurement.

To minimize oxidation, samples were wrapped in aluminum foil before heating. The foils were removed before the measurements were carried out. After the test period, the oxidation of the samples was checked by microscopic examination and no oxidation was found.

During the aging process, the samples were kept in aluminum plate sample holders, where the distance between individual samples was more than 50 mm. This was to minimize the effect of external magnetic field caused by other samples.

Room temperature BH curves were measured for each type of sample material and the coercivities were determined from these curves. The coercivity values listed in Table 1 represent points where the BH curves start to bend downwards. These coercivity values are used to identify different samples in section 3.

#### Table 1. Room temperature coercivities of the samples.

<table>
<thead>
<tr>
<th>Material</th>
<th>Coercivity (kA/m)</th>
<th>Dy content</th>
<th>Co addition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1240</td>
<td>1 %</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1700</td>
<td>4 %</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1850</td>
<td>4 %</td>
<td>x</td>
</tr>
<tr>
<td>4</td>
<td>1900</td>
<td>7.5 %</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>&gt; 3000</td>
<td>11.5 %</td>
<td></td>
</tr>
</tbody>
</table>

### III. Results and Discussion

Magnetization losses as a function of time for materials without Co addition are plotted in Figures 1 – 10. Each plotted point represents an average loss of 3 – 6 identical samples measured at a time. Besides the measurement points, the logarithmic trend curves are plotted to show the average loss behavior.

#### A. Room temperature

At room temperature, no losses were found in any of our samples. Loss trends for samples with the lowest coercivity values are presented in Figure 1.
B. Temperature 60°C

At a temperature of 60°C, there were only small differences found in the trend slopes for samples with the lowest permeance coefficient values. The slope for the low coercivity material ($H_{ci} = 1240$ kA/m) differed clearly from zero (see fig. 2.), but losses are still within 2 % after 8 000 hours.

![Figure 2. Magnetization losses as a function of time at 60°C. Permeance coefficient of the samples, $P_c = 0.33$.](image)

C. Temperature 80°C

Only one type of sample, the one with the lowest coercivity and smallest permeance coefficient showed clear losses at 80°C. There were losses of over 8 % already after one hour as can be seen in Fig. 3. and the following slope went down quite fast. In the same material, almost zero losses occur at 80°C when the permeance coefficient was raised to 1.1 (see Fig. 4).

![Figure 3. Magnetization losses as a function of time at 80°C. Permeance coefficient of the samples, $P_c = 0.33$.](image)

D. Temperature 120°C

At a temperature of 120°C the material with coercivity $H_{ci} = 1240$ showed severe losses in samples with $P_c = 0.33$ and $P_c = 1.1$ (Fig. 6), but when $P_c = 3.3$ losses were within 3 % after 8 000-hour period (Fig. 7). For the material $H_{ci} = 1700$, the initial loss in $P_c = 0.33$ samples was around 3 % (Fig. 5), but the trend slope was quite steep and the loss after 8 000-hour period was as much as around 10 %. However, when the $P_c$ was > 1.1, also in this material, losses became negligible (< 1 %).

![Figure 5. Magnetization losses as a function of time at 120°C. Permeance coefficient of the samples, $P_c = 0.33$.](image)
E. Temperature 150°C

A temperature of 150°C is clearly too high for most of the samples with low Pc (= 0.33). Only the material Hci > 3000 kA/m has almost a horizontal trend curve (Fig. 8). Even though a similar initial loss in material Hci = 1900 occurred, the slope of the trend curve was steeper. The difference between these two materials is not so clear when Pc = 1.1 (Fig. 9). Additionally the material Hci = 1700 showed a fairly horizontal trend curve when Pc = 3.3 (Fig. 10).
F. Co addition

With Co addition, the room temperature coercivity can be raised from 1700 kA/m to 1850 kA/m in material containing 4% dysprosium. This also had an effect on the long-term polarization loss behavior. In Figure 11, the loss trends of these two materials are compared. The aging temperature of these samples was 120°C. The improvement of stability by Co addition is the clearest in samples where the Pc = 0.33.

![Figure 11. Comparison of the magnetization losses in materials with 4% Dy. Hci = 1850 was achieved with Co addition. Aging temperature = 120°C.](image-url)

IV. Conclusion

The combination of the Hci and Pc of a permanent magnet determines its maximum operating temperature. In addition to the reversible magnetization loss due to temperature change, irreversible losses occurring in magnets need to be considered in motor design. There are irreversible losses that occur as soon as a certain temperature is reached and a thermal after-effect, which means losses with time.

In most of the cases, the amount of immediate loss predicts the slope of the following trend curve. This is due to the fact that when the working point of a magnet falls below the knee of the BH curve, the magnetization becomes unstable. Immediate losses occur and the losses with time will also increase. In some cases the slope of the trend curve cannot be predicted from the immediate loss. For example, at 150°C, two materials (Hci = 1900 and Hci > 3000) in Pc = 0.33 samples showed a similar immediate loss, but the slope of the following trend curve was clearly different.

The main objective of this study was to demonstrate that negligible losses with time are possible in designs where the operating point of the magnet is above the BH curve knee. These results give engineers a better opportunity to optimize their permanent magnet circuits and to choose a suitable magnet material for the application.

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REFERENCES