<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *IEEE transactions on magnetics*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Sjökvist, S., Eriksson, S. (2014)

Experimental Verification of a Simulation Model for Partial Demagnetization of Permanent Magnets.

IEEE transactions on magnetics, 50(12)

<http://dx.doi.org/10.1109/TMAG.2014.2339795>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-236307>

Experimental Verification of a Simulation Model for Partial Demagnetization of Permanent Magnets

Stefan Sjökvist¹ and Sandra Eriksson¹

¹Division for Electricity, Department of Engineering Sciences,
Uppsala University, Box 534, 75121 Uppsala, Sweden

This article aims to verify a FEM simulation model for demagnetization of permanent magnets. The model is designed to determine the remaining magnetization within the permanent magnet after it has been exposed to high demagnetizing fields and/or temperature. An experimental set-up was built and a permanent magnet of SmCo type was experimentally tested. Good agreement is shown between the simulation and experimental results. A maximal deviation of 3 % of the simulation results in relative to the experimental results were achieved for most part of the magnet. During the calibration of the simulation model it was found that the coercivity had to be significantly more negative compared to the permanent magnet's reference value to match simulation results to the experimental results.

Index Terms—Simulation, FEM, Permanent magnet, Demagnetization, SmCo.

I. INTRODUCTION

WHEN designing any type of permanent magnet (PM) electrical machine, the magnet type and grade are considered in an early stage of the design process [1]. First, regarding rotor type, for permanent magnets with high energy product (BH_{max}), e.g. NdFeB or SmCo, a surface mounted rotor could be used. If permanent magnets with lower performance are to be used, e.g. Ferrites or Alnico, a field concentrating pole shoe rotor may be required to achieve the desired flux. The rotor/magnets need to produce the required flux for the machine to reach the desired torque or induced voltage. This can be achieved by choosing a permanent magnet with a high remanence (B_r). At the same time the magnet should not be demagnetized under periods of high load, which is why a high intrinsic coercivity (H_{cJ}) usually is desired. Unfortunately, these material properties are strongly related to one another and it is hard to achieve both at the same time. However, research is being conducted in the area of material design, trying to increase both these properties [2], [3].

A properly designed permanent magnet machine will remain fully magnetized during normal operation and after the most common fault events. Uncommon and more severe fault events are not always necessary to protect against, since other parts of the machine may be heavily damaged and/or the whole machine needs to be

replaced anyway. These and many other parameters have to be considered when designing a permanent magnet machine.

This article is focused on the demagnetization risk for the permanent magnets. The aim is to experimentally verify a finite element method (FEM) model originally presented in [4]. The demagnetization model is based on an exponent function model presented by Ruoho et al. [5] and the approach is similar to Kang et al. [6] and Kim et al. [7]. With relatively low magnetic fields the demagnetization curve ($M-H$, the magnetization and magnetic field, respectively) only need to be modelled in the second quadrant [8], i.e. the permanent magnet is not expected to be magnetized in the opposite direction. The objective with the FEM model is to determine if and how much permanent magnets will be demagnetized when exposed to a high demagnetizing field and/or temperature. The model is to be used as a design tool, for testing geometries with different magnet grades under non-normal operation conditions, i.e. for finding the optimal combination of geometry and magnetic materials.

Further development have been made to the model since it was originally presented in [4]. The main improvement is the ability to determine the remaining magnetization of the magnet when the demagnetizing field and/or temperature are returned to their original values. This change is further described in section II.

II. DEVELOPMENT OF FEM MODEL

The FEM model presented in [4] has been developed to simulate permanent magnets in electrical machines

Fig. 1: Demagnetization curve with original **B-H** curve and recoil curve after demagnetization has occurred, calculated by the simulation software.

during user defined operational conditions. The model can handle both 2D and 3D geometries and is developed in the commercially available FEM software Comsol Multiphysics. A 3D model may be used when large leakage fluxes are expected which cannot be modelled in 2D. Time varying effects such as eddy currents are not considered in either the 2D or 3D model.

For this study the FEM model has been improved to calculate the magnetization after the surrounding environment has been restored to normal condition. Further, the model can now also handle inhomogeneous temperatures inside the magnets, meaning that each point inside the magnets will have its own shape of the **B-H** curve.

The remaining magnetization is calculated by saving the state of the magnet at the instant of the event. With the **B** and **H** field from this moment the magnet can be examined for demagnetization. The saved values of **B** is compared to the original **B-H** curve. The recoil magnetization of the permanent magnets is calculated with a linear model. The recoil is approximated to a straight line parallel to the initial slope of the original **B-H** curve. The new remanence can therefore be expressed as

$$B_r^{new} = B^s - \mu_0 \mu_r \cdot H^s \quad (1)$$

where, B^s and H^s are the saved values of the magnetic flux density and the magnetic field, respectively, in the examined point of the permanent magnet. If the current working point of the magnet is in the linear part of the original **B-H** curve, then the same remanence will be achieved. An example figure of how the demagnetization model works is shown in Fig. 1.

Although the recoil curve will experience a slight bend

Fig. 2: Schematic drawing of the iron core used in the experiments, all dimensions are in mm. The out of plane thickness is 85 mm

upwards the linear model used and presented here is considered to be good enough [9], [10].

III. EXPERIMENTAL SET-UP

The experimental set-up consists of a rectangular shaped iron core with a side length of 400 mm and 550 mm, respectively, all dimensions are shown in Fig. 2. The total thickness of the iron core is 85 mm and was constructed from 1 mm sheets of M700-100A laminated steel. The magnet sample will be placed in the 17 mm opening on the right leg. A 423 turn coil of 6 mm² copper cable was wound around the right and the lower leg of the iron core.

The coil was connected to a power supply (EA-PS 8160-170) capable of delivering a direct current of 170 A. The current source was manually controlled during the experiments.

The magnet samples that were to be tested were placed one by one in the 17 mm opening. The magnet samples had a height of 14 mm, leaving a 3 mm air gap.

A. Magnets

The tested permanent magnet grade was a Sm₂Co₁₇ 30L, data for the magnet grade is presented in Table I [11]. The permanent magnets were bought magnetized and no control measurements were

TABLE I: Data of the permanent magnets (at 20°C) provided by the manufacturer [11].

Grade	B_r	H_c	H_{cJ}	$(BH)_{max}$
	(T)	(kA/m)	(kA/m)	(kJ/m ³)
SM30L	1.08-1.12	477-557	493-716	223-247

performed beforehand. No data was found on the recoil permeability, μ_r , for this specific grade so a value of 1.0 was used in the simulations. The dimensions of the magnets were 74x54x14 mm.

B. Measuring probe holder

In order to measure the magnetic flux density in the air gap with high reproducibility a measuring probe holder was 3D printed in polylactide (PLA) plastics. The probe holder had 10 slots where the measuring probe could be placed. The slots were distributed along a line perpendicular to the air gap on the 54 mm side of the magnet. The corners of the probe holder were extended to ensure a tight fit around the magnet. In this way the measuring probe holder was placed in the middle of the air gap and in the exact same position relative to the magnet in each measurement and high reproducibility could be achieved. Using the probe holder also ensures that only the magnetic flux density parallel to the length of the air gap, $B_{||}$, is measured. A Hall sensor probe on a Gauss-meter (F.W. BELL 5180) was used to measure the magnetic flux density in the experiments.

IV. CALIBRATING SIMULATIONS AND EXPERIMENTS

A. Iron properties

The **B-H** curve of the M700-100A steel was control measured in an Epstein frame at the manufacturer. The measured curve was used in all simulation of this study. However, when measuring $B_{||}$ 2 mm above the bottom side of the air gap as a function of current in the coil, the experiments and simulations did not perfectly match. In Fig. 3 the simulation and experimental results are compared. As can be seen in the figure the simulation underestimate the magnetic flux density at low currents and over estimates it at high. The reason for this, even though the **B-H** curve was control measured, is that it is really hard to know how the steel behaves in the rolling and transverse direction, RD and TD respectively. Also, how the magnetic field is influenced by the angle relative the RD is not know. When measuring in an Epstein frame equal amount of steel from the RD and TD is used. Hence, only a mean value of the **B-H** curve is achieved. In this experimental set-up the RD is in the horizontal direction of Fig. 2. In other words the magnetic field

Fig. 3: The experimental and simulation results of $B_{||}$ as a function of Ampere turns without a permanent magnet in the magnetic circuit. The dark line represents results from simulations and the light line experimental results.

has to travel a longer way in the TD than in the rolling direction. At the same time the field in the RD would probably be higher than in the simulation. These issues could probably be a big reason for the deviation between the results.

B. Remanence

The data of the magnet in Table I are in the span of which the manufacturer promises to deliver. The actual values should be anywhere within these limits and may vary between samples. To compensate for this, each tested magnet was placed in the magnetic circuit and $B_{||}$ was measured. The remanence of the magnet in the simulation model was then changed until good agreement between the experimental and the simulated results had been accomplished. Further, different small currents were sent through the coil and $B_{||}$ (in a single point) was measured simultaneously to verify how well the simulated values followed a measured curve. Only small currents were used to make sure that the magnet only operated in its linear region. A plot of $B_{||}$ for different currents from experiments and simulations is depicted in Fig. 4.

As can be seen in the linear part of Fig. 4, the simulated curve has a bit lower slope than the slope of the experimental curve. This is probably due to the different slope of the curves in Fig. 3.

C. Coercivity and intrinsic coercivity

To calibrate the PMs in the simulation model further, higher currents were sent through the coil in the simulations so that the magnet would go into its non-linear

Fig. 4: The magnetic flux density in one point in the air gap with a PM, as a function of applied current. The dark line is simulation results and the light line is experimental results of the same experiment.

region. The same was done in the experimental set-up. $B_{||}$ was measured simultaneously, resulting in the non-linear part of Fig.4. After replacing the PM, since it now had been partly demagnetized, $B_{||}$ was measured before and after a PM was demagnetized in the experimental set-up. The PM was demagnetized with a current of 30 A or 12690 Ampere-turns. The coercivity and the shape of the knee of the **B-H** curve of the PM in the simulation model was adjusted until good agreement was achieved for $B_{||}$ in both Fig. 4 and after demagnetization of the PM. One can see in the non-linear part of the Fig. 4 that the line from the simulated results will cross the experimental line at about 12 kA turns. This is probably related to the fact that the simulated flux is overestimated at high currents as seen in the top part of Fig. 3.

When calibration of the PMs parameter was done, the adjusting of the remanence and the intrinsic coercivity for other samples was done in the following way. When the remanence of another sample had been determined the percentage change was calculated and then the intrinsic coercivity was changed the same amount. It was assumed that the remanence and the intrinsic coercivity had the same rate of change when designing a new **B-H** curve from the calibrated curve, i.e. if the remanence was lowered 5% then the intrinsic coercivity was lowered 5%.

V. EXPERIMENTS

Even though inhomogeneous temperatures can be simulated with the FEM model, no accurate way was found to determine and describe the temperature distribution inside the magnet during experiments. Instead, the surrounding temperature, close to the magnet, was measured

TABLE II: The input data to the FEM model for all the samples.

Sample	B_r (T)	H_c (kA/m)	H_{cJ} (kA/m)
1	0.975	-716	-807
2	0.951	-697	-787
3	0.970	-712	-803

and used as the magnets homogeneous bulk temperature. This was considered accurate enough under the given circumstances. In every measurement, four series were measured, the average value was then used.

A total of 3 magnets were tested in the following way.

- 1) The magnet was placed in the opening in the iron core and $B_{||}$ was measured in all ten positions in air gap.
- 2) A current of 30 A (12690 Ampere-turns) was fed through the coil.
- 3) $B_{||}$ was measured again when the current had been returned to zero.

VI. RESULTS

Result of sample 1 and 2 are depicted in Fig. 5. The plots show simulation and experimental results for $B_{||}$ before and after demagnetization. The experimental results (the dots) are the mean value of four individual measurements on each position. In Table II the input data to the FEM model is presented. The constant K_1 which describes the shape of the knee [4], [5] was set to $-0.28 \cdot 10^{-4}$ m/A. The surrounding temperature was 20°C.

VII. DISCUSSION

In Fig. 5 it can be seen that the simulation results from after demagnetization matches the experimental results well especially around the center of the magnet. If neglecting the two outer points of the experimental results the maximal deviation of the simulation results from the experimental is 3 %, for the after demagnetization results. The maximal deviation of the after demagnetization results is 17.8 %. These results also includes the third sample that is not plotted here.

The maximum deviation of simulation results and experimental results before demagnetization was 7.9 %. It can be seen in Fig. 5 that the largest deviation in results between the simulations and the experiments does not occur at the edges of the magnet, but rather about a quarter of the way in. The main reason for this is that the simulations were adjusted until good agreement was found for the middle points of the experimental results. Alternatively, the adjustment of the simulation results

Fig. 5: $B_{||}$ as a function of position relative the magnet. The lines are simulations results and the dots are experimental results. The dark lines and dots are before demagnetization and the light are after demagnetization. Lines are results from simulations and dots are experimental results.

could have taken into account a wider area and hence lowering the deviations at these points.

The reason for the bigger deviations of the results at the edges after demagnetization could be a consequence that the simulation model only takes into account the component of the magnetic flux density parallel to the magnetization direction.

The remanence of the PMs differed more than expected, none of the tested PMs were within the limits given by the manufacturer. Some of the magnets with lower remanence also showed an uneven magnetization distribution, especially after demagnetization. These magnets were excluded from the study with the motivation that they were damaged from the start and no satisfactory starting conditions could be achieved.

The reference values of the coercivity and the intrinsic coercivity provided by the manufacturer were not achieved either, a more negative (better) value of them both were needed to achieve a satisfactory **B-H** curve, as was presented in Table II. This means that the PMs are harder to demagnetize than what the data sheet of the PMs suggested, which usually is a good feature. Using the assumption that the remanence and coercivity has the same rate of change and using the values from the calibration, the values of the coercivity and the intrinsic coercivity at saturation ~ 1.1 T would be -815 kA/m and -911 kA/m, respectively. Which is significantly better than the reference values of Table I.

VIII. CONCLUSIONS

As shown by a comparison of Tables I and II, good modelling of the measurements required that the average model intrinsic coercivity had to be 11.6% larger in

amplitude than the largest value in the manufacturer's specification and the magnet remanence had to be 10.6% smaller than the smallest value in the specification. From the results it can be concluded that the simulation model performs well and can predict demagnetization behaviour accurately. The simulations and experiments gives similar results for most parts of the magnet.

IX. ACKNOWLEDGEMENTS

This work was carried out with funding from the Swedish Research Council, grant number 2010-3950 and within the StandUP for Energy strategic research framework.

The authors would also like to thank Dr. A. Broddefalk at Surahammars Bruks AB for the control measurement of the electrical steel.

REFERENCES

- [1] N. Domann, W.-R. Canders, and M. Henke, "Design process and topology comparison for a high performance pm-machine for sustainable traction drive technology," in *Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER)*, 2013.
- [2] J. Liu, T. Ohkubo, K. Hioki, A. Hattori, T. Schrefl, and K. Hono, "Effect of nd content on the microstructure and coercivity of hot-deformed Nd-Fe-B permanent magnets," *Acta Materialia*, vol. 61, pp. 5387–5399, June 2013.
- [3] H. Sepehri-Amin, J. Liu, T. Ohkubo, K. Hioki, A. Hattori, and K. Hono, "Enhancement of coercivity of hot-deformed Nd-Fe-B anisotropic magnet by low-temperature grain boundary diffusion of Nd-Dy-Cu eutectic alloy," *Scripta Materialia*, vol. 69, pp. 647–650, July 2013.
- [4] S. Sjökvist and S. Eriksson, "Study of demagnetization risk for a 12 kw direct driven permanent magnet synchronous generator for wind power," *Energy Science and Engineering*, vol. 1, no. 3, pp. 128–134, 2013. [Online]. Available: <http://dx.doi.org/10.1002/ese3.16>

- [5] S. Ruoho, E. Dlala, and A. Arkkio, "Comparison of demagnetization models for finite-element analysis of permanent-magnet synchronous machines," *IEEE Transactions on Magnetics*, vol. 43, no. 11, pp. 3964–3968, December 2007.
- [6] G.-H. Kang, J. Hur, H. Nam, J.-P. Hong, and G.-T. Kim, "Analysis of irreversible magnet demagnetization in line-start motors based on the finite-element method," *IEEE Transactions on Magnetics*, vol. 39, no. 3, pp. 1488–1491, May 2003.
- [7] K.-C. Kim, S.-B. Lim, D.-H. Koo, and J. Lee, "The shape design of permanent magnet for permanent magnet synchronous motor considering partial demagnetization," *IEEE Transaction on Magnetics*, vol. 42, no. 10, pp. 3485–3487, October 2006.
- [8] D. Xie, W. Zhang, B. Bai, L. Zeng, and L. Wang, "Finite element analysis of permanent magnet assembly with high field strength using preisach theory," *IEEE Transactions on Magnetics*, vol. 43, no. 4, pp. 1393–1396, April 2007.
- [9] S. Ruoho and A. Arkkio, "Partial demagnetization of permanent magnets in electrical machines caused by an inclined field," *IEEE Transactions on Magnetics*, vol. 44, no. 7, pp. 1773–1778, August 2008.
- [10] H. C. Lovatt and P. A. Watterson, "Energy stored in permanent magnets," *IEEE Transactions on Magnetics*, vol. 35, no. 1, pp. 505–507, January 1999.
- [11] Sura Magnets AB, <http://www.suramagnets.se/>, retrieved November 5th, 2013.