Demagnetization Studies on Permanent Magnets
-
Comparing FEM Simulations with Experiments

Stefan Sjökvist
Abstract

In a world where money often is the main controlling factor, everything that can be tends to be more and more optimized. Regarding electrical machines, developers have always had the goal to make them better. The latest trend is to make machines as efficient as possible, which calls for accurate simulation models where different designs can be tested and evaluated. The finite element method is probably the most popular approach since it makes it possible to, in an easy and accurate way, get numerical solutions to a variety of physics problems with complex geometries and non-linear materials.

This licentiate thesis includes two different projects in which finite element methods have had a central roll. In the first project, the goal was to develop a simulation model to be able to predict demagnetization of permanent magnets. It is of great importance to be able to predict if a permanent magnet will be demagnetized or not in a certain situation. In the worst case, the permanent magnets will be completely destroyed and the machine will be completely useless. However, it is more probable that the permanent magnets will not be completely destroyed and that the machine still will be functional but not as good as before. In a time where money is more important than ever, the utilization has to be as high as possible. In this study the demagnetization risk for different rotor geometries in a 12 kW direct driven permanent magnet synchronous generator was studied with a proprietary finite element method simulation model. The demagnetization study of the different rotor geometries and magnet grades showed that there is no risk for the permanent magnets in the rotor as it is designed today to be demagnetized. The project also included experimental verification of the simulation model. The simulation model was compared with experiments and the results showed good agreement.

The second project treated the redesign of the rotor in the generator previously mentioned. The goal was to redesign the surface mounted NdFeB rotor to use a field concentrating design with ferrite permanent magnets instead. The motivation was that the price on NdFeB magnets has fluctuated a lot the last few years as well as to see if it was physically possible to fit a ferrite rotor in the same space as the NdFeB rotor. A new rotor design with ferrite permanent magnets was presented together with an electromagnetic and a mechanical design.

Keywords: Permanent magnet, demagnetization, simulation, FEM, Comsol Multiphysics, VAWT

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To "The Scientist"
List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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The author presented parts of the work from paper II at the conference Magnetic Materials in Electrical Machine Applications 2012 in Pori, Finland, 13-15 June 2012.

The author has also contributed to the following paper, not included in this thesis:


*The author changed his surname from Larsson to Sjökvist in July 2013.
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<td>Magnetic vector potential</td>
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<td>Magnetic flux density</td>
</tr>
<tr>
<td>$B_\delta$</td>
<td>[T]</td>
<td>Amplitude of magnetic flux density in air gap</td>
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<tr>
<td>$B_{max}$</td>
<td>[T]</td>
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<td>Remanence</td>
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<td>$BH_{max}$</td>
<td>[kJ/m$^3$]</td>
<td>Maximum energy product</td>
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<tr>
<td>c</td>
<td>-</td>
<td>Number of parallel circuits</td>
</tr>
<tr>
<td>$D_{si}$</td>
<td>[m]</td>
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<tr>
<td>E</td>
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<tr>
<td>$H_c$</td>
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<td>[A]</td>
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<tr>
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<td>$H_{ic}$</td>
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</tr>
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</tr>
<tr>
<td>$n_s$</td>
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</tr>
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</tr>
<tr>
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<td>[Wb]</td>
<td>Magnetic flux</td>
</tr>
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<td>[W]</td>
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<tr>
<td>$P_{Cu}$</td>
<td>[W]</td>
<td>Total copper loss</td>
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<tr>
<td>$P_{Fe}$</td>
<td>[W]</td>
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<tr>
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<td>Description</td>
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<tr>
<td>$P_{Fe,ed,\text{loss}}$</td>
<td>[W/kg]</td>
<td>Specific loss due to eddy currents in generator core</td>
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<td>$P_{Fe,ex,\text{loss}}$</td>
<td>[W/kg]</td>
<td>Excess loss in generator core</td>
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<td>$P_{Fe,hy,\text{loss}}$</td>
<td>[W/kg]</td>
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<td>$q$</td>
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<td>$R_p$</td>
<td>[Ω]</td>
<td>Phase resistance</td>
</tr>
<tr>
<td>$U_{p,rms}$</td>
<td>[V]</td>
<td>Phase voltage, rms</td>
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<tr>
<td>$T$</td>
<td>[K]</td>
<td>Temperature</td>
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### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>DDPMSG</td>
<td>Direct Driven Permanent Magnet Synchronous Generator</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>NdFeB</td>
<td>Neodymium-Iron-Boron</td>
</tr>
<tr>
<td>PM</td>
<td>Permanent Magnet</td>
</tr>
<tr>
<td>RD</td>
<td>Rolling Direction</td>
</tr>
<tr>
<td>SmCo</td>
<td>Samarium-Cobalt</td>
</tr>
<tr>
<td>TC</td>
<td>Temperature coefficient</td>
</tr>
<tr>
<td>TD</td>
<td>Transverse Direction</td>
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</table>
1. Introduction

Permanent magnets (PMs) are today widely used as a field source in electrical machines. Compared to electrical machines with field windings, permanent magnets have the advantage of no losses in excitation system, lower weight, higher torque and/or output power, lower maintenance and a simplification of the machine construction. Also, permanent magnet machines generally have higher efficiency than their field wound counterparts [1–3]. There are numerous types of electrical machines which use permanent magnets as magnetic field source [4–6].

Lower weight (smaller size) and a simplification in the machine construction implies less material use which leads to less energy consumption in the manufacturing process. Together with high output power and efficiency permanent magnet machines seems like the perfect choice. Unfortunately, the production of high performance, especially Neodymium-Iron-Boron (NdFeB), permanent magnets has a high environmental impact and the price has been very unstable the last several years. Regardless of these negative aspects there are room for improvement, hence, it is still worth the investment to develop permanent magnet electrical machines.

When designing any type of permanent magnet electrical machine, the magnet type and grade are considered in an early stage of the design process. First, regarding rotor type, for permanent magnets with high energy product (BH$_{\text{max}}$), e.g. NdFeB or Samarium-Cobalt (SmCo), a surface mounted rotor could be used. If lower performance permanent magnets are to be used, e.g. Ferrites or Alnico, a field concentrating pole shoe rotor may be required to achieve the acquired flux. The rotor/magnets need to produce the required flux for the machine to reach the desired torque or induced voltage. At the same time the magnet can not be damaged (demagnetized) under periods of high load. Unfortunately, these material properties are strongly related to one another and it is hard to get both at the same time. However, research is being conducted in the area of material design, trying to increase both these properties [7,8]. More on magnetic material properties is presented in section 2.1.2.

During the design process the demagnetization risk is considered, at least for normal working conditions and preferably for the most common cases of unexpected load. The arguments for not examining all possible demagnetization scenarios are cost and if the worst case scenario would occur other parts of the machine would be destroyed and
the machine might need to be replaced anyway. The demagnetization process has been studied for a long time and for numerous applications and situations [9–12]. While a great deal of research have been made on the demagnetization process of permanent magnets, many researchers have been using proprietary software or have not mentioned the software [13–15] i.e the software is not necessarily available for commercial use. In this thesis the basics of a proprietary model, developed in a commercially available software, is presented and evaluated by comparison with experimental results. By using a commercial available software it shows the industry that accurate results can be achieved without the need for a proprietary simulation software.

1.1 Background of the Wind Power Project

The work presented in this thesis is a part of a wind power project at Uppsala University. The project started in 2002 with the vision of developing a mechanical simple and low maintenance wind power concept. The vision resulted in the idea with a vertical axis H rotor turbine. The turbine is omnidirectional and can therefore extract wind from all direction, making a yaw system excessive. The turbine is passively stall regulated which makes a pitch system for the blades unnecessary. Further, the turbine is connected to a direct driven synchronous permanent magnet generator (DDPMSG) which is placed on ground level. Placing the generator and other heavy components on the ground level reduces stress on the turbine tower and makes generator maintenance easier. The wind power group has to date designed and produced; three complete wind power plants with turbine and generator and one experimental lab generator. One prototype, a 12 kW vertical axis wind turbine, built in 2006, can be seen in figure 1.1.

While much work within the group has been conducted on the aerodynamics, electrical system, mechanical properties and generator design, the magnetic material properties have not been studied in these machines. The work presented in this thesis does not cover the ageing of permanent magnets but rather what happens to the permanent magnets during unlikely events when high demagnetizing field can occur, for example, during a short circuit in the electrical system.

1.2 Aims of this Thesis

The aims of this thesis are to gain more knowledge on demagnetization behaviour in electrical machines and to evaluate a finite element method (FEM) model by comparing it with experimental results. The work in
this thesis is a step towards a design tool for selecting permanent magnets and designing electrical machines.

1.3 Outline of the Thesis

The thesis begins with a brief theory chapter containing permanent magnet material properties and a description of the developed FEM model. Thereafter, the different studies that have been conducted are presented in chapter 3 followed by a results and discussions chapter. Finally, some conclusions and suggested future work are presented.
2. Theory

The following chapter gives a theoretical overview to the different areas presented in this thesis, mainly focusing on generator theory and 2D analysis using finite elements.

2.1 Generator

2.1.1 General theory

A generator consists of a rotating part (rotor) and a stationary part (stator). The rotor is magnetized either with a field winding and current or with permanent magnets. The stator experiences an alternating magnetic field when the rotor rotates relative to it. The rotating field induces a variable voltage in the stator winding. From Faraday’s law of induction we know that the induced voltage $E_i$ in a coil is proportional to the number of turns ($N$) in the coil and the rate of change of the magnetic flux ($\Phi$) as

$$E_i = -N \frac{d\Phi}{dt}.$$  \hspace{1cm} (2.1)

In a generator the winding consists of a series of coils, the induced voltage of all these coils sums up to the total induced voltage in the winding. Generally, a generator consists of more than one phase, i.e. more than one winding. The induced voltage in a winding also depends on how the coils are positioned in the generator relative to each other. A good approximation on how the rms phase voltage ($U_{p,rms}$) depends on the generator design properties is given by

$$U_{p,rms} = \frac{\pi}{\sqrt{2}} f_r p q n_s c^{-1} B_\delta l_{br} D_{si} f,$$ \hspace{1cm} (2.2)

where $f_r$ is the winding factor, $p$ is the number of poles, $q$ is the number of slots per pole and phase, $n_s$ is the number of conductors per slot, $c$ is the number of parallel circuits, $B_\delta$ is the amplitude of the magnetic flux density in the air gap, $l_{br}$ is the length of the stator, $D_{si}$ is the inner diameter of the stator and $f$ is the rotor’s mechanical frequency.

Eq. (2.2) is generally called the Generator formula and is often used to approximate the design of a generator. It can also be used to study different variables influence on the generator performance. The generator
build for the vertical axis wind turbine shown in figure 1.1 has been
designed, built and tested [16]. FEM simulation results of that generator
geometry showed rms phase voltage of 167 V and the experiments 161 V.
Applying the generator formula on that 12 kW generator, assuming a
stacking factor of 0.95, gives \( U_{p,rms} = 166.4 \) V. This result show that
the Generator formula over estimates the voltage since it among others
does not consider any losses, more on losses in section 2.1.3, but it is still
a good approximation early in the design process.

2.1.2 Magnetic Material
Magnetic material in a permanent magnet generator comprises more
than just the magnets. In a generator, magnetic material includes all
parts that are designed to conduct a magnetic field. These parts can also
be called active material. This section is mainly based on information
from [17].

The B-H curve
A ferro magnetic material is usually characterized by its B-H curve, where \( B \) is the magnetic flux density and \( H \) is the magnetic field. The
B-H curve describes how the magnetic flux density in a material varies
with an externally applied magnetic field. Two important material prop-
erties can be extracted from the B-H curve; the remanence \( (B_r) \) and the
coercivity \( (H_c) \). After a material has been saturated by an external mag-
netic field, the remanence is the remaining magnetic flux density in the
material after the external applied field is removed. The coercivity is
a measure of how high external applied field is needed to reduce the
internal magnetic flux density of the material to zero.

From an electrical machine’s perspective, there are two types of mag-
netic material; first there are the so called hard magnetic materials that
are characterized by high remanence and high coercivity. The second
material type is characterized by low remanence and low coercivity and
is therefore called soft magnetic. Example drawings of B-H curves for
a hard and a soft magnetic material are depicted in figure 2.1. A low
coercivity enables the magnetic field to easily rotate inside the material,
which is a good property for stator steel, in which the magnetic field ro-
tates with the same frequency as the electrical frequency of the machine.
When the field has completed one lap it has in the same time completed
one lap on the B-H curve and has been subjected to a phenomena called
hysteresis. To lower the hysteresis losses, the coercivity should be as low
as possible. Hysteresis losses are discussed more in section 2.1.3.
Permanent magnet materials

Permanent magnets are generally hard magnetic, i.e. they have high coercivity and high remanence. As mentioned above, the coercivity is a measure of how high an external magnetic field is needed to reduce the magnetic flux density inside the material to zero. However, this value does not necessarily mean that the magnetization of the material is reduced to zero. A good magnet grade will not lose any magnetization when the magnetic flux density is reduced to zero. The necessary field strength to reduce the magnetization to zero is denoted $H_{ic}$ and called the intrinsic coercivity, an example figure of how the magnetic polarization ($J_m = \mu_0 M$) and the magnetic flux density is related to an external field is depicted in figure 2.2. The demagnetization curve in figure 2.2 is sometimes called the intrinsic B-H curve since the same plot can be achieved by plotting $B - \mu_0 H$ vs. $H$.

All materials have some property that change with temperature, magnetic materials are no exception. Generally, the temperature coefficient of the remanence is negative for all magnetic materials, meaning that the remanence decreases with increasing temperature. The temperature coefficient of coercivity depends on the material. Ferrites and Alnico have a positive coefficient, meaning that the coercivity increases with increasing temperature, whereas it is negative for other magnetic materials.

2.1.3 Losses

Generators suffer from mechanical and electromagnetic losses. The mechanical losses consist of frictional losses in bearings, couplings and air. The electromagnetic losses are mainly divided into two categories; iron
and copper losses,

\[ P_{loss} = P^{Fe}_{loss} + P^{Cu}_{loss}. \] (2.3)

Iron losses can further be divided into hysteresis, eddy current and excess losses each of which will be discussed below.

Hysteresis loss is a complex phenomena that were briefly mentioned in section 2.1.2. Here hysteresis losses will be discussed in a somewhat simplified way. A magnetic material such as non-oriented silicon steel, commonly used in electrical machines, consists of very small magnetic domains. Inside these domains all magnetic dipole moment are parallel, i.e. the domains can be seen as small permanent magnets randomly oriented inside the material. Since they are randomly oriented the net magnetization of the material is zero. When an external magnetic field is applied these magnetic domains start to rotate and align themselves parallel to the applied magnetic field, the material becomes magnetized. When the applied field is removed most of the domains will return to their original position but a few will remain in their changed position. This results in a small but permanent magnetization of the material. The reason for this resulting magnetization is due to the friction between the magnetic domains, more energy is needed to move them back to their original positions. Now, to reach the same field strength in the opposite direction the applied field needs to be a bit higher than the initial, e.g. some extra work is needed to change the position of the domains that did not change back to their original position and align them in the opposite direction. This extra work needed is generally denoted as hysteresis loss [18].

The total hysteresis loss when an applied field has rotated 360° is the enclosed area of the corresponding B-H curve. From empirical studies...
the hysteresis loss is proportional to the maximum magnetic flux density during a cycle and is approximated according to

\[ P_{Fe,hy}^{loss} = k_h B_{max}^\beta f_{el}, \] (2.4)

where \( k_h \) is a material specific constant, \( B_{max} \) is the amplitude of \( B \), \( \beta \) is the Steinmetz number, also a material constant and \( f_{el} \) is the electrical frequency. Typical values for a laminated silicon iron are in the ranges \( k_h = 40-55, \beta = 1.8-2.2 \) [19–22]. All specific iron losses are given in W/kg and have to be multiplied with the total weight of the stator to find the total loss.

The eddy current losses in the stator are induced in the same way as in the armature windings. The specific eddy current loss is from empirical studies approximated to

\[ P_{Fe,ed}^{loss} = k_c B_{max}^2 f_{el}^2, \] (2.5)

where

\[ k_c = \frac{\pi^2 \sigma d^2}{6 \rho_c}, \] (2.6)

where \( \sigma \) is the conductivity, \( d \) is the laminated sheet thickness and \( \rho_c \) is the mass density of the stator core. As seen from Eq. (2.5) and Eq. (2.6) the eddy currents is reduced by decreasing the thickness and conductivity of the core lamination sheets [19,22].

The last component of the iron losses is the excess loss, also called anomalous loss. The excess loss is caused by the domain wall motion as the domain structure changes when a magnetic field is applied and described as

\[ P_{Fe,ex}^{loss} = k_e B_{max}^{3/2} f_{el}^{3/2}, \] (2.7)

where \( k_e \) is the excess loss coefficient. The excess loss is somewhat debated since good total loss agreement can be achieved when \( k_e = 0 \) [19,22]. This results in the following expression for the total iron losses

\[ P_{Fe}^{loss} = m_s (k_h B_{max}^\beta f_{el} + k_c B_{max}^2 f_{el}^2 + k_e B_{max}^{3/2} f_{el}^{3/2}), \] (2.8)

where \( m_s \) is the total weight of the stator core.

The copper losses are divided into resistive and eddy current losses. Resistive losses are due to the inner resistance of the copper cable. The eddy current losses in the windings is usually small due to the low permeability of copper and denoted in a similar way as for the stator core. In a three phase machine the total copper losses can be expressed as

\[ P_{Cu}^{loss} = 3 R_p I_{p}^2 + P_{Cu,ed}^{loss}, \] (2.9)

where \( R_p \) is the phase resistance, \( I_p \) is the phase current and \( P_{Cu,ed}^{loss} \) is the eddy current losses inside the cables.
2.2 2D Analysis of Electrical Machine using Finite Elements

The purpose of using finite element analysis (FEA) on an electrical machine is to calculate the magnetic field distribution of the machine. For symmetry reasons, it is usually sufficient to model a limited region of the machine. Further, in many cases, depending on the problem, it is often sufficient to model a 2D cut section of the machine. An example geometry of such a case is shown in figure 2.3. The results can be integrated over the total length of the machine to get the induced voltage.

Using a 2D representation of a 3D problem has some drawbacks, 3D effects such as eddy currents and end effect of the machine can not be modelled. This section is mainly based on material from [23], [13] and [24].

![Example machine geometry used in a FEM model.](image)

Figure 2.3. Example machine geometry used in a FEM model.

2.2.1 Derivation of Field Equation

Magnetostatic problems can be described by the two following differential equations

\[ \nabla \times \mathbf{H} = \mathbf{J} \]  \hspace{1cm} (2.10)

\[ \nabla \cdot \mathbf{B} = 0 \]  \hspace{1cm} (2.11)

where, \( \mathbf{J} \) is an external current density. Since the model is for static cases all components of the electric field (\( \mathbf{E} \)) has been neglected.
\( \mathbf{B} \) and \( \mathbf{H} \) are related according to

\[
\mathbf{B} = \mu_0 \mu_r \mathbf{H} \tag{2.12}
\]

where, \( \mu_0 \) is the permeability for vacuum and \( \mu_r \) is the relative permeability for the material. From definition we know that

\[
\mathbf{B} = \nabla \times \mathbf{A} \tag{2.13}
\]

where \( \mathbf{A} \) is called the magnetic vector potential. If we assume the problem to be in 2D with the geometry in the xy-plane, we know from Eq. (2.10) that the current density only has a z-component. From Biot-Savart’s law

\[
\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_{V'} \frac{\mathbf{J}(\mathbf{r'})}{R} dV' \tag{2.14}
\]

it can be seen that the magnetic vector potential also only has a z-component. In Eq. (2.14), \( V' \) is the volume in space where the current density is non-zero and a distance \( R \) from the point where \( \mathbf{A} \) is evaluated.

To reduce the number of unknowns, the problem can be expressed in terms of \( \mathbf{A} \). By using Eq. (2.13) and Eq. (2.12) on Eq. (2.10), one arrives at

\[
\nabla \times (\mu_0 \mu_r)^{-1} \nabla \times \mathbf{A} = \mathbf{J} \tag{2.15}
\]

By applying some vector algebra on Eq. (2.15) and since we know \( \mathbf{A} \) and \( \mathbf{J} \) only have z-components, we finally arrive at

\[
-(\mu_0 \mu_r)^{-1} \nabla^2 A_z = J_z \tag{2.16}
\]

which is the equation solved using a FEM software.

### 2.2.2 Boundary Conditions

In order for the field problem to be fully defined, boundary conditions has to be defined on the boundaries of the geometry. Three different boundary conditions have been used, which all will be given a short explanation. The first, set on the inner and outer boundaries of the example geometry is the \textit{homogeneous Dirichlet boundary condition}

\[
A_z = 0. \tag{2.17}
\]

A \textit{homogeneous Dirichlet boundary condition} is equivalent of an insulating boundary condition, e.g. no flux is allowed through the boundary.

In a perfectly round and concentric electrical machine the geometry exhibits a repetitive feature. The size of the simulated geometry can be
reduced to the smallest repeatable part by including periodic continuity boundary conditions which relate the value of $A_z$ on two equivalent boundaries to each other.

The last boundary condition used is a sector symmetry boundary condition or moving boundary condition. This is set on the boundary that represents the air gap between the rotor and the stator. The sector symmetry boundary condition works in a similar way as the periodic boundary condition with the addition of movement (without re-meshing) along the boundary. In figure 2.4 all appropriate boundary conditions are applied to the example geometry first introduced in figure 2.3.

2.2.3 Method for Irreversible Demagnetization Analysis

To model the demagnetization of magnets the relationship between $B$, $H$ and $M$ for the magnets is needed. This relationship is easiest described with a $B$-$H$ curve and the constitutive relation

$$B = \mu_0(H + M). \tag{2.18}$$

A $B$-$H$ curve can be modelled with an analytic function [13]

$$B = B_r + \mu_0 \mu_r H + E e^{K_1(K_2+H)} \tag{2.19}$$

where, $B_r$ is the remanent flux density, $\mu_0$ is the permeability, $\mu_r$ is the relative permeability and $E$ is a unit conversion factor and it is 1 T. The parameter $K_2$ is calculated from:

$$K_2 = \frac{\ln \left( (B_r + (\mu_r - 1) \cdot \mu_0 \cdot H_{ic}) \cdot E^{-1} \right)}{K_1} - H_{ic}. \tag{2.20}$$

The $K_1$ parameter sets the shape of the knee point in the $B$-$H$ curve, where a larger value gives a sharper knee. Good agreement with several
NdFeB magnet grades was found with a $K_1$ value of $-1.5 \cdot 10^{-4}$ m/A. The magnetization can then be calculated with Eq. (2.18).

As seen in Eq. (2.19)-(2.20) the only material parameters needed to approximate the $B$-$H$ curve is the remanence and the coercivity. PM manufacturers often provides the temperature coefficient (TC) for these parameters which makes it possible to reproduce a $B$-$H$ curve for any give temperature. The temperature coefficient is often given in $[\%/\degree K]$ which would allow $B_r$ and $H_{ic}$ to be rewritten as

$$B_r^T = B_r + (B_r \cdot k_B \cdot (T - 293.15)) \quad (2.21)$$
$$H_{ic}^T = H_{ic} + (H_{ic} \cdot k_H \cdot (T - 293.15)) \quad (2.22)$$

where, $T$ is the temperature in K, $k_B$ and $k_H$ are the temperature coefficients for the remanence and the intrinsic coercivity, respectively.

**Recoil**

The recoil magnetization of the permanent magnets is calculated by a linear model [25]. The recoil is approximated to a straight line parallel to the initial slope of the $B$-$H$ curve, the slope is

$$k = \mu_0 \cdot \mu_r \quad (2.23)$$

The new remanence can therefore be expressed as

$$B_{r newest} = B_s - k \cdot H^s \quad (2.24)$$

where, $B_{now}$ and $H_{now}$ are the current values of the magnetic flux density and the magnetic field, respectively. If the current working point of the magnet is in the linear part of the $B$-$H$ curve, the same remanence will be achieved. If the working point has dropped below the knee point this will result in a new value of the remanence. Also, a new $B$-$H$ relationship is calculated by using Eq. (2.20) and Eq. (2.19).
3. Method

3.1 Demagnetization Risk of a 12 kW DDPMSG

In paper II an early version of the simulation model was used to study the demagnetization risk for different magnet grades in a 12 kW DDPMSG. This paper was written before the simulation model was verified and before the magnetization recoil, presented in section 2.2.3, was implemented.

The study included three different permanent magnet grades, one grade with similar properties to the one used in the built generator and two others. One aim with the study was to see if the cost of permanent magnet could be reduced. Therefore, both of the other permanent magnet grades included in the study were cheaper than the one used in the built generator. Another way to reduce the use of permanent magnet material is to reduce the magnet size. When reducing the magnet size the air gap has to be reduced to retain the same magnetic flux density. Hence, an alternative rotor geometry was suggested. The idea was to reuse the same stator. The magnets on the alternative rotor was reduced in height from 14 mm to 6.5 mm and the total weight reduced from 41 kg to 19 kg. The air gap was reduced from 10 mm to 5 mm. Data on the permanent magnets used in this study is presented in table 3.1 [26]. Magnet A is the one similar to the magnet in the existing generator.

Three different magnet grades were simulated for two different generator geometries. In total, six unique generators were simulated. All generators were tested for the same cases, normal load and during a two phase short circuit, both at 20°C and 60°C. The short circuit current ($I_{sc}$) was determined for each generator using the FEM model [16] used for designing the generator. In the short circuit simulations, the current in one phase was set to $I_{sc}$ and the other phases were set to $-I_{sc}/2$. Further, to find the worst possible position of the rotor during the short

<table>
<thead>
<tr>
<th>Magnet (Vacodym)</th>
<th>B$_r$ (T)</th>
<th>H$_c$ (kA/m)</th>
<th>H$_{ic}$ (kA/m)</th>
<th>BH$_{max}$ (kJ/m$^3$)</th>
<th>TC (% B$_r$/°C)</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - 633 TP</td>
<td>1.32</td>
<td>1020</td>
<td>1432</td>
<td>335</td>
<td>-0.095</td>
<td>1</td>
</tr>
<tr>
<td>B - 745 HR</td>
<td>1.44</td>
<td>1115</td>
<td>1200</td>
<td>400</td>
<td>-0.115</td>
<td>0.95</td>
</tr>
<tr>
<td>C - 722 HR</td>
<td>1.47</td>
<td>915</td>
<td>955</td>
<td>415</td>
<td>-0.095</td>
<td>0.89</td>
</tr>
</tbody>
</table>
Table 3.2. Typical values for the selected magnet used in the study, at 20°C.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>$B_r$ (T)</th>
<th>$H_c$ (kA/m)</th>
<th>$H_{ic}$ (kA/m)</th>
<th>$BH_{max}$ (kJ/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM30L</td>
<td>1.08-1.12</td>
<td>-477-557</td>
<td>-493-716</td>
<td>223-247</td>
</tr>
</tbody>
</table>

circuit, each geometry was simulated at different stationary positions. The rotor was rotated with an angle of $1^\circ$ (16 el$^\circ$) per simulation, with a total rotation of $45^\circ$ (720 el$^\circ$). More detail regarding the simulations can be found in paper II.

3.2 Verification of Simulation Model

In paper I the latest version of the simulation model was verified, which includes the irreversible demagnetization analysis, as described in section 2.2.3. To verify the model the simulation results were compared to experimental results. For this purpose, a simple geometry was designed and constructed. The idea was that the experimental set-up should be mechanically simple and easy to do analytical calculations on. In the simulation part of the study a 3D model was used.

In this study one magnet grade was tested, the SmCo grade SM30L. Data for the magnet is presented in table 3.2 [27].

3.2.1 Experimental Set-up

The experimental set-up consisted of a rectangular shaped iron core with a side length of 400 mm and 550 mm, respectively. All dimensions are shown in figure 3.1. The total thickness of the iron core is 85 mm and it 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 mm$^2$ 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 was placed one by one in the 17 mm opening, the magnet samples had a height of 14 mm, leaving a 3 mm air gap. The area where the permanent magnet samples were placed is 10 mm wider in both directions, with respect to the magnet samples. This was done to get the magnetic field more even inside the magnet during high fields.
3.2.2 Measuring probe holder
To measure the magnetic flux during the experiments a Gauss-meter (F.W. BELL 5180) was used. On the tip of the measurement probe there is a Hall sensor which measures the magnetic field perpendicular to the measurement probe. The probe is angular sensitive, it is therefore critical to always hold the probe perpendicular to the direction you want to measure. 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. Using the probe holder also ensures that only the magnetic flux density parallel to the length of the air gap, $B_{||}$, was measured.

3.2.3 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 figure 3.2 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 known. 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 figure 3.1. In other words the magnetic field 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 explain the deviation in the results.

3.2.4 Remanence

The data of the magnet in table 3.2 are in the span of which the manufacturer promises to deliver. The actual values should be anywhere within these limits but may vary between samples. To compensate for this variation, 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.

As can be seen in the linear part of figure 3.3, 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 figure 3.2.
Figure 3.3. 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.

3.2.5 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 region. The same was done in the experimental set-up. $B_{||}$ was measured simultaneously, resulting in the non-linear part of figure 3.3. 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 $\mathbf{B}$-$\mathbf{H}$ curve of the PM in the simulation model was adjusted until good agreement was achieved for $B_{||}$ in both figure 3.3 and after demagnetization of the PM. One can see in the non-linear part of figure 3.3 that the line from the simulated results will cross the experimental line at about 12 kA turns. This is probably related to that the simulated flux is overestimated at high currents as seen in the top part of figure 3.2.

When calibration of the PM’s parameters was done, adjustments of the remanence and the intrinsic coercivity for other samples were 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 accordingly, i.e. it was assumed that the remanence and the intrinsic coercivity had the same rate of change when designing a new $\mathbf{B}$-$\mathbf{H}$ curve from the calibrated curve.

3.2.6 Experiments
In the experiments, a total of three 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 the air gap.
2) A current of 30 A (12690 Ampere-turns) was led through the coil.
3) $B_{||}$ was measured again when the current had been returned to zero.

In every measurement four series were measured and the average value of these was used.

3.3 Redesign of a 12 kW DDPMSG

Paper III addresses the redesign of the 12 kW DDPMSG studied in paper II. The generator is further described in [16, 28]. The goal with this project was to completely redesign the rotor of the generator, to use ferrite permanent magnets instead of NdFeB. The motivation for this is the unstable price developments for NdFeB the last few years and to see if it is possible to achieve the same electrical properties for the generator.

Further, the redesign involves the mechanical structure of the rotor as well as the electromagnetic circuit.

Ferrites have about 1/3 of the remanence and approximately 1/10 of the energy product of NdFeB. To achieve the same air gap flux density approximately 10 times more ferrite material is needed than NdFeB. This could be a problem since the stator of the generator would be reused, i.e. there could be a space issue to fit the required amount of ferrites.

Initially in the design process the properties of ferrite magnets were investigated and a rough design was made. With a rough design proposal, the mechanical design could commence. From this point on the design was an iterative process, when the mechanical limitations were reached the electromagnetic design was changed and vice versa.
4. Results and Discussion

In the following chapter the most important results form the papers are presented and discussed.

4.1 Demagnetization Risk of a 12 kW DDPMSG

Results from paper II are summarized in table 4.1. The A magnet has similar properties to the grade used in the built generator. Case 1 and 2 are normal load and short circuit, respectively, both at 20°C. Case 3 and 4 are the same as case 1 and 2 but at an elevated temperature of 60°C. The denotation ”(thin)” refers to the presented alternative geometry with thinner magnets and smaller air gap. The table includes the minimum value of the magnetic field inside the magnets for all the angles that were tested, i.e. the worst result for every geometry. The gray background in some of the cells of table 4.1 indicates that the magnets will be partly irreversible demagnetized. In figure 4.1 the minimum value of the magnetic field is plotted versus the rotational angle (Θ) of the rotor, for each grade C magnet in case 4. The horizontal line represents the knee point value of the permanent magnet’s B-H curve. The right figure of figure 4.1 represents the remaining magnetization expressed in % of the original magnetization (M₀) for Mag.1 at 0.018 rad.

The results from this study show that there is no risk of demagnetizing the magnets in the generator as it is built. Using the same magnet

Table 4.1. The minimum magnetic field inside the magnets for all simulation cases and rotor positions. Gray background indicates that the magnets will be partly irreversibly demagnetized. I_sc is the maximum amplitude of the short circuit current. The presented price only represents the price of the PMs. δ_rated is the load angle.

<table>
<thead>
<tr>
<th>Grade</th>
<th>H^{mag}_{min} (kA/m)</th>
<th>I_sc (A)</th>
<th>δ_rated (°)</th>
<th>Price (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case 1</td>
<td>Case 2</td>
<td>Case 3</td>
<td>Case 4</td>
</tr>
<tr>
<td>A</td>
<td>-498</td>
<td>-742</td>
<td>-467</td>
<td>-716</td>
</tr>
<tr>
<td>A (thin)</td>
<td>-570</td>
<td>-945</td>
<td>-533</td>
<td>-914</td>
</tr>
<tr>
<td>B</td>
<td>-550</td>
<td>-799</td>
<td>-520</td>
<td>-753</td>
</tr>
<tr>
<td>B (thin)</td>
<td>-632</td>
<td>-1023</td>
<td>-598</td>
<td>-774</td>
</tr>
<tr>
<td>C</td>
<td>-561</td>
<td>-806</td>
<td>-515</td>
<td>-611</td>
</tr>
<tr>
<td>C (thin)</td>
<td>-644</td>
<td>-942</td>
<td>-586</td>
<td>-617</td>
</tr>
</tbody>
</table>
grade it would also be possible to reduce the air gap to 5 mm and the magnet height to 6.5 mm without compromising the magnets during a 2 phase short circuit. The other magnet grades, B and C, performed well but it is hard to motivate the use of these since the price difference is almost negligible. The best way to decrease the cost would be to use the alternative rotor geometry. This could however result in increased cost of support structure and tolerances when building the rotor.

4.2 Verification of Simulation model

Simulation and experimental results of $B_{||}$ before and after demagnetization for sample 1 and 2 are depicted in figure 4.2. The experimental results (the dots) are the mean value of four individual measurements on each position. In table 4.2 the input data of the samples to the FEM model is presented. The data was collected during calibration of each

<table>
<thead>
<tr>
<th>Sample</th>
<th>$B_r$ (T)</th>
<th>$H_c$ (kA/m)</th>
<th>$H_{ic}$ (kA/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.975</td>
<td>-716</td>
<td>-807</td>
</tr>
<tr>
<td>2</td>
<td>0.951</td>
<td>-697</td>
<td>-787</td>
</tr>
<tr>
<td>3</td>
<td>0.970</td>
<td>-712</td>
<td>-803</td>
</tr>
</tbody>
</table>

Table 4.2. The input data to the FEM model for all the samples.

$\Theta$ (rad)

Figure 4.1. The minimum magnetic field inside the magnets as a function of rotational angle relative to the stator (left). The horizontal line represents the value of the demagnetization point. A plot of the remaining magnetization in the worst affected magnet, Mag. 1, at angle 0.018 rad (right).
sample as described in section 3.2. The constant $K_1$ which describes the shape of the knee of the $B$-$H$ curve [13] was set to $-0.28 \cdot 10^{-4}$.

In figure 4.2 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 results after demagnetization. The maximal deviation of the results after demagnetization is 17.8 %. These results of the deviation also includes the third sample that is not depicted here.

The maximum deviation of simulation results and experimental results before demagnetization was 7.9 %. It can be seen in figure 4.2 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, giving a larger deviation of the results at these positions. Alternatively, the adjustment of the simulation 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 of that the simulation model only takes into account the component of the magnetic flux density parallel to the magnetization direction.
4.2.1 Deviation of remanence and coercivity

The remanence of the PMs differed more than expected. None of the tested PMs were in the limits given by the manufacturer, see table 3.2. This could relate to that the PMs had been stored in their original shipping boxes for about two years. The variation between each sample also differed much, some had a remanence as low as 0.7 T while the best was at about 0.97 T. 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 tabled interval values of the coercivity and the intrinsic coercivity provided by the manufacturer could not be satisfied. A lower value of both were needed to achieve a satisfactory B-H curve, as presented in table 4.2. From the initial calibration the coercivity and the intrinsic coercivity was -566 kA/m and -650 kA/m, respectively. The remanence of this magnet was 0.785 T. This means that the PM is 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 $\sim 1.1$ T would be -815 kA/m and -911 kA/m, respectively, which is significantly lower than the tabled values of table 3.2.

4.3 Redesign of a 12 kW DDPMSG

The characteristics of the new rotor designed in paper III is compared to the old rotor in table 4.3. As can be seen in the table the electrical properties of the generator with the new rotor is somewhat different from the original design. Due to the lower air gap flux density, the induced voltage is decreased and a higher armature current is needed to maintain the same output power. By doing so, the resistive losses increase. However, due to the decreased air gap flux density the iron losses is lowered. Together, the total loss is only slightly increased compared to the original generator. Furthermore, since ferrite permanent magnets are used, the mass of the rotor has increased more than three times.
Table 4.3. A comparison of the generator characteristics for the old (NdFeB) and new (Ferrite) design. Values are at rated load and speed. All values are from simulations except for the weights of the old design. Some information of the magnets used is also included.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>NdFeB rotor</th>
<th>Ferrite rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power [kW]</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Phase voltage, no load, rms [V]</td>
<td>172</td>
<td>146</td>
</tr>
<tr>
<td>Phase voltage, rms [V]</td>
<td>167</td>
<td>141</td>
</tr>
<tr>
<td>Armature current, rms [A]</td>
<td>23.9</td>
<td>28.5</td>
</tr>
<tr>
<td>Armature current density, rms [A/mm(^2)]</td>
<td>1.49</td>
<td>1.78</td>
</tr>
<tr>
<td>Amplitude of air gap flux density fundamental at no load [T]</td>
<td>0.79</td>
<td>0.66</td>
</tr>
<tr>
<td>Resistive losses [W]</td>
<td>275</td>
<td>390</td>
</tr>
<tr>
<td>Iron losses [W]</td>
<td>254</td>
<td>159</td>
</tr>
<tr>
<td>Electromagnetic efficiency [%]</td>
<td>95.8</td>
<td>95.6</td>
</tr>
<tr>
<td>Minimum air gap [mm]</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Mass of rotor [kg]</td>
<td>130</td>
<td>407</td>
</tr>
<tr>
<td>Mass of PM [kg]</td>
<td>41</td>
<td>158</td>
</tr>
<tr>
<td>Moment of inertia [kg m(^2)]</td>
<td>16.9</td>
<td>34.2</td>
</tr>
<tr>
<td>PM material grade</td>
<td>N40</td>
<td>Y40</td>
</tr>
<tr>
<td>Remanence of PM [T]</td>
<td>1.27</td>
<td>0.45</td>
</tr>
<tr>
<td>Maximum energy product [kJ/m(^3)]</td>
<td>310</td>
<td>47.6</td>
</tr>
</tbody>
</table>
5. Conclusions

Summary of conclusions drawn from the research presented in this thesis.

In paper I, a proprietary FEM model, developed in a commercially available software, was compared to experimental results. Simulation results showed good agreement with the experimental results and it was concluded that the simulation model can predict demagnetization accurately.

In paper II, a simulation based study where three different grades of NdFeB permanent magnets were investigated in two different rotor geometries of a 12 kW DDPMSG. According to the results there is no risk of demagnetizing the rotor of the 12 kW DDPMSG used in the study with its original rotor and permanent magnets. It would be possible to reduce the magnet size and still almost achieve the same electrical properties. However, when changing the geometry and magnet grade there is a risk for partial demagnetization of the permanent magnets.

The study presented in paper III focused on the design aspects of changing a rotor with surface mounted NdFeB permanent magnets of a 12 kW DDPMSG, to a flux concentrating rotor with ferrite permanent magnets. A new rotor design that can be used in the same stator and still retain similar electrical properties was presented. The reduced air gap flux density results in a decreased induced voltage which is compensated with a higher current. The rated power is kept the same but the efficiency is somewhat reduced due to increased resistive losses.
6. Suggested Future Work

6.1 Eddy current losses on the PM and rotor surfaces
Eddy current losses on the surface of permanent magnet are almost always neglected since the field is assumed to be stationary. However, in some machines this could be a problem which could result in a temperature increase of the permanent magnets, which in turn would experience a shift of the working point in the affected areas.

6.2 Demagnetization due to shock
Permanent magnets can be demagnetized when exposed to shocks. However, finding information about this phenomena is hard. A study on this topic would be interesting since the magnets can be subjected to rather high shocks during the assembly of a rotor. This is mainly a concern when the assembly is done by hand. When the magnet is moved close to the iron surface the magnet will be attracted to this surface and it can be difficult to gently set down the magnet. The shock when the magnet hits the iron surface can be rather high and might result in partial demagnetization of the permanent magnet.

6.3 Demagnetization risk due to inclined fields
The model presented in paper I and II only considers the magnetic flux density parallel to the magnetization direction. Earlier studies show that this is sufficient in multi pole machines [9] where the load angle is low. However, if other machines need to be studied the inclination of the field needs to be considered.

Unfortunately the magnetic flux density’s influence on the demagnetization is not a \( \cos(\alpha) \) relationship, where \( \alpha \) is the field inclination angle with respect to the magnetization direction. Therefore, each magnet’s angular relationship needs to be experimentally obtained before it can be implemented into the simulation model.
Denna licentiatavhandling behandlar framför allt avmagnetisering av permanentmagneter men har även ett kort avsnitt om designprocessen för en permanentmagnetiserad generator.


Om vi tar exemplet med en permanentmagnetiserad generator, i dessa är det permanentmagneterna som ger upphov till magnetfältet i generatorn. Rotationshastigheten och fältets styrka är direkt proportionerligt mot den inducerade spänningen i generators lindning. Vill man ta ut en konstant effekt ur generatorn så beror alltså strömmen på hur stor den inducerade spänningen är. Minskar spänningen t.ex. p.g.a. att permanentmagneterna delvis har avmagnetiserats så måste man öka strömmen för att bibehålla samma uteffekt. En ökad ström ger ökade resistiva för- luster, vilket i sin tur leder till att temperaturen stiger i generator. En ökad temperatur kan i värsta fall leda till att magneterna avmagnetiseras ytterligare och vi hamnar då i en ond cirkel där högre och högre ström måste dras för att bibehålla samma uteffekt. Detta kan komma att fortsätta tills all isoleringen på kablarna smälter och vi får kortslutning om inte styrsystemet upptäcker den ökande strömmen och stänger ner generatorn.

Arbetet i denna licentiatavhandling handlar om utvecklingen av en simuleringsmodell där permanentmagneter kan testas i olika lastfall för att se om de kommer att skadas. Tanken med denna simuleringsmodell är att den ska kunna fungera som ett designverktyg för att dimensionera den magnetiska kretsen samt välja ut den bäst lämpade permanentmagnetssorten. Mer specifikt har en studie gjorts för att verifiera att simuleringsmodellen stämmer bra överens jämfört med experiment. En
simuleringsbaserad studie har även gjorts på en specifik 12 kW direkt-driven permanentmagnetiserad synkrongenerator. I den studien testades tre olika typer av NdFeB magneter och två olika rotor geometrier för att undersöka vilka magneter som skulle avmagnetiseras i olika lastfall.

Till sist så har även en designstudie gjorts för att undersöka om rotorn i den ovan nämnda 12 kW generatorn går att byta ut till en rotor med ferrit magneter. Motiveringen till varför man skulle vilja göra detta är för att priset på materialen som används i NdFeB permanentmagneter har varierat mycket de senaste åren, även om det för tillfället har varit ganska stabilt en tid. Ferritmagneter har inga sällsynta jordartsmetaller i sig och blir därmed inte lika priskänsliga som NdFeB magneter. nackdelen med ferritmagneter är att dessa är mycket svagare än NdFeB magneter och en speciell typ av rotor måste konstrueras för att fokusera det magnetiska fältet från två eller flera magneter för att uppnå samma flöde som med NdFeB magneter. Detta leder till att rotorn växer och att det kan bli svårt att få plats med allt på samma utrymme som den tidigare rotorn. Projektet lyckades och det finns en färdig mekanisk och elektromagnetisk design över den nya generatorn, ombyggnationen planeras att börja under sommaren/hösten 2014.
8. Summary of Papers

Paper I

Experimental Verification of a Simulation Model for Demagnetizing of Permanent Magnets

This paper aims to experimentally verify the simulation model first presented in paper II. Further development was made to the model since it was originally presented. The main improvement was that a function for the magnetic recoil behaviour was added. To experimentally verify the simulation model an iron core with a coil capable of producing high magnetic field was designed and built. The experimental set-up was modelled in the simulation software and the experimental and simulation results were compared. Results showed that the simulation model performed well and can predict demagnetization behaviour accurately. The simulations and experiments gave similar results for most parts of the magnet.

The author did the majority of the work.

The paper was submitted to IEEE Transactions on Magnetics, April 2014.

Paper II

Study of Demagnetization Risk for a 12 kW Direct Driven Permanent Magnet Synchronous Generator for Wind Power

In this paper the first version of the simulation model analysing demagnetization of permanent magnets is presented. The paper also consists of a simulation based study of the use of different, cheaper, permanent magnet grades in a 12 kW DDPMSG designed and constructed by the research group. Further, an alternative geometry was suggested to study if less permanent magnet material could be used without the risk of demagnetization. Results showed that the only magnet grade that was not demagnetized during any of the assumed cases for both geometries was the one used in the built generator.

The author did the majority of the work.

The paper was published online in Energy Science & Engineering, September 2013, doi:10.1002/ese3.16.
Paper III

A Complete Design of a Rare Earth Metal-Free Permanent Magnet Generator

This paper addresses the redesign of the rotor for a 12 kW DDPMSG. The main objective was to design a completely new rotor with ferrite permanent magnets instead of a rotor with NdFeB as in the existing generator. The design includes both electromagnetic and mechanic design and the electromagnetic properties should be as close to the old design as possible. A completely new design of a rotor with ferrite magnets is presented. Simulations show comparable results to the old design even though the air gap flux is reduced. To keep the same output power the current needs to be increased slightly.

The author was supervisor of the master thesis the paper is based on and was involved in the planing, execution of the project and writing of the paper.

The paper was published in Machines, May 2014, doi:10.3390/machines2020120
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