Thermal Properties of a Prototype Permanent Magnetized Electrical Motor Embedded in a Rim Driven Thruster

Øystein Krøvel  Knut Andresen  Normann Sandøy

Abstract — For machine designs it is usually the thermal limits that sets the boundaries for how high the power density of a machine can be. This paper shows calculations of losses and temperatures together with temperature measurements on a 100 kW surface mounted radial flux permanent machine (SM RFPM). The special feature of this machine is that it is totally enclosed in water, which yields very good cooling. The measurements confirm this.

I. INTRODUCTION

Traditionally podded propulsion and thrusters use hub driven propellers with either motor in the hub, or a shaft through the hull. Rim driven solutions are usually used mainly in small machines as remote operated vehicles (ROV’s) and some smaller ships, and usually with radial support with a shaft through the centre of the propeller ([1]-[3]).

The idea of the rim-driven-thruster (RDT) concept is to connect the blades of the thruster to an outer ring, rather than a hub. A large diameter PM-motor fulfils this demand by making the rotor hollow. In 2002-2003 a prototype 100kW rim driven thrust in without shaft, was built ([4] and [5]). The motor housing is fully enclosed by water, which gives very good cooling and a possibility for high electrical loading. This paper presents analytical calculations and finite element analysis (FEA) of the stator losses and measurements of the temperatures in the stator windings on the 100kW RDT prototype.

II. ANALYTICAL LOSS CALCULATION

A. Copper Losses

The DC- resistance of one phase is:

\[ R_{DC} = \frac{N_c \cdot N \cdot l_{turn}}{A_{turn} \cdot \sigma_{Cu}} \]  

Where \( N_c \) is number of coils in series, \( N \) the number of turns pr coil, \( l_{turn} \) the length of one turn, \( A_{turn} \) the area of one turn, and \( \sigma_{Cu} \) the conductivity of copper. The conductivity is given at a temperature \( T_0 \), assuming \( T_n \) in the winding at nominal conditions a temperature coefficient can be found from [6]:

\[ k_T = \frac{234 + T_0}{234 + T_n} \]

The machine is wound with round copper wire. Based on [7] the AC-coefficient for the resistance is:

\[ \frac{D_{cond}}{\delta_{skin}} = \sqrt{\pi \cdot f \cdot H_c \cdot \sigma_{Cu}} < 1.5 \]

Where \( D_{cond} \) is the conductor diameter and \( \delta_{skin} \) the skin depth. This results in the copper losses:

\[ P_{Cu} = 3 \cdot \frac{k_{AC} \cdot R_{DC} \cdot I^2}{k_T} \]

B. Iron Losses, Analytic

The iron losses can be estimated using data given in the datasheet from the manufacturer of the stator lamination [8] based on simple analytical equations for flux densities.

\[ \hat{B}_g = B_g \cdot \frac{l_m}{l_m + g} \]

\[ \hat{B}_s = \frac{2 \cdot \hat{B}_g}{\pi} \]

\[ \hat{B}_c = \hat{B}_g \cdot \frac{\tau_s}{w_s} \]

\[ \hat{B}_{sc} = \frac{\hat{B}_g \cdot \tau_m}{2 \cdot w_{sc}} \]

\( l_m \) is the magnet length, \( g \) the air gap length, \( B_g \) the remanent flux density of the magnet, \( B_s \) the air gap flux density, \( \tau_s \) the slot pitch, \( w_s \) the slot width, \( \tau_m \) the magnet pitch and \( w_{sc} \) the core depth. ^ and – denotes amplitude and mean values. The tooth and stator core flux is found in (5). Using the flux densities and frequency the losses can be interpolating from the data sheet values.
C. Iron Losses, FEA

Using a FEA tool the flux density is found in the teeth and core. Using the flux density and the frequency the losses can be calculated from empiric data provided from the supplier of the lamination [8].

Fig. 1 Flux density in the stator with magnet directly over the centre tooth. The grid indicates the area used to calculate the core losses.

The stator can be divided into two parts: The teeth and the core. Studying Fig. 1 it can be seen that the tooth in the middle (which is directly under a magnet) has its maximum flux density in this instant. And for all points one can assume this to be the amplitude value. Using the nominal frequency, the amplitude of the flux density and the empirical data from the manufacturer a plot of the loss distribution can be made (Fig. 2).

Fig. 2 Loss distribution in tooth at nominal speed.

The amplitude and shape of the flux density in the core can be found by examine the area indicated by the grid in Fig. 1 and rotating the rotor. Fig. 3 shows the plots of the tangential and radial component of the flux density as a function of position at some points in the core. Each plot shows the curve for five different radii at three different angles from the tooth center.

It is assumed that the two components of the flux density induce losses independently in the lamination (B\(_{\text{rad}}\) in the tangential-axial plane and B\(_{\text{tan}}\) in the radial-axial plane). The amplitude values of the two components are plotted in Fig. 4. Using the mean value of the loss distribution in the core, the core loss can be found.

Fig. 3 Circular plot for three different tangential position. Top: over the center of the tooth, Bottom: Over the center of the slot, Middle: in between.

The content of harmonics in the different curves has been examined to look for higher order losses. M. La has in [9] presented more accurate calculations for iron losses in IPMSM and SynRM investigating the harmonics of the rotating field. Fig. 5 shows the harmonics for the square (#2) curve at the top in Fig. 3. This is one of the curves that have the highest component of harmonics. And as can be seen the harmonics are low. The harmonics contributions to the losses are therefore neglected.
The thermal model is established to calculate the temperature rise in the machine.

A. The model

The thermal model is based on Grauers thermal network presented in [9] and most of the material properties are from his work. An admittance matrix is generated and solved with a tool similar to those used for solving electrical networks. This eliminates the need to simplify the circuit before generating the admittance matrix.

The thermal network is presented in appendix (VII). Some simplifications can be done. Both rotor and stator are covered with composite materials and it is assumed that there is no heat transferred to or through the air gap. Due to the lamination the heat flow is assumed to be only in radial and tangential direction in the stator.

B. Heat transfer coefficients and thermal insulations in the machine

Both copper and iron are good heat conductors. It will therefore be the electrical insulation and air in the winding that will contribute to the temperature gradients. The thermal properties of the materials used are listed in Table 1. \( \lambda_{\text{coil}} \) is the conductivity in radial and tangential direction in the coil. This is low since the machine is wound by hand and not vacuum painted. \( \alpha_{\text{end}} \) is the transfer coefficient in the area around the end windings.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Thermal Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{\text{Cu}} )</td>
<td>conductivity copper W/K.m 400</td>
</tr>
<tr>
<td>( \lambda_{\text{coil}} )</td>
<td>cond. coil W/K.m 0.45</td>
</tr>
<tr>
<td>( \lambda_{\text{ins}} )</td>
<td>cond. slot insulation W/K.m 0.2/0.15</td>
</tr>
<tr>
<td>( \lambda_{\text{Fe}} )</td>
<td>cond. iron W/K.m 38</td>
</tr>
<tr>
<td>( \alpha_{\text{end}} )</td>
<td>trans. to air W/K.m(^2) 15</td>
</tr>
<tr>
<td>( \rho_{\text{water}} )</td>
<td>density water kg/m(^3) 1000</td>
</tr>
<tr>
<td>( \mu_{\text{water}} )</td>
<td>viscosity water kg/ms 1.8*10(^{-5})</td>
</tr>
<tr>
<td>( \beta_{\text{water}} )</td>
<td>expansion coefficient 1/K 2.1*10(^{-4})</td>
</tr>
<tr>
<td>( C_{p,\text{water}} )</td>
<td>thermal capacitance J/kgK 1005</td>
</tr>
<tr>
<td>( \lambda_{\text{water}} )</td>
<td>cond. water W/K.m 0.0257</td>
</tr>
</tbody>
</table>

The heat transfer coefficient to water is dependent of the speed of the water. The equations used are presented in (6)-(10).

\[
Re = \frac{\rho_{\text{water}} \cdot V_{\text{water}} \cdot L}{\mu_{\text{water}}} \tag{6}
\]

\[
Gr = \frac{\rho_{\text{water}}^2 \cdot g \cdot \beta_{\text{water}} \cdot \Delta T \cdot L^3}{\mu_{\text{water}}} \tag{7}
\]

\[
Pr = \frac{C_{p,\text{water}} \cdot \mu_{\text{water}}}{\lambda_{\text{water}}} \tag{8}
\]

\[
Nu = 0.0296 \cdot Re^{0.8} \quad \text{if} \quad Re > 5 \cdot 10^5
\]

\[
Nu = 0.53(Gr \cdot Pr)^{0.25} \quad \text{if} \quad Re < 5 \cdot 10^5 \tag{9}
\]

D. Evaluation of loss calculations

The simplified iron loss calculations do not take into account the leakage of magnet flux, and in this case there will be some leakage between the tooth tips. This result in a approximately 25% higher calculated losses with the simplified model. Both methods presented here uses the no load flux in the machine. This is a fairly good approximation for this type of machine with low reactance. The load current will only in a small degree affect the flux from the magnets and the effect will mostly be to twist the curves to either side depending on the load angle.
\[ \alpha_{\text{water}} = \frac{Nu \cdot \lambda_{\text{water}}}{L} \]  \hspace{1cm} (10)

L is the machine length and Re, Gr, Pr and Nu respectively the Reynolds, Grasshoff, Prandtl and Nusselt numbers.

C. Calculated Temperatures

Based on the loss calculations from section II, the thermal model can be used to estimate the temperature rise in the machine. In Table 2 the calculated temperature rises at nominal speed and current are presented.

<table>
<thead>
<tr>
<th>Position</th>
<th>( P_{i, \text{FEA}} )</th>
<th>( P_{i, \text{ana}} )</th>
<th>( \lambda_{\text{ins}} = 0.2 )</th>
<th>( \lambda_{\text{ins}} = 0.15 )</th>
<th>( \lambda_{\text{ins}} = 0.15 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot top</td>
<td>59</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slot bottom</td>
<td>53</td>
<td>61</td>
<td>62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil end</td>
<td>58</td>
<td>67</td>
<td>67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tooth top</td>
<td>12</td>
<td>11</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tooth bottom</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stator core</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the thermal calculations it can be seen that the main thermal gradient is the electric insulation in the slot. The changes in water speed or heat transfer coefficient has little effect since the heat transfer is very good for all speeds. A change in the iron loss does not change the temperature in the winding much, this because of the good cooling to the sea through iron.

IV. MEASUREMENTS

The measurements of the temperature rise in the machine were done during testing of the machine in the sea during comparable conditions. The temperatures were measured with PT100 elements embedded in the windings. The temperatures were measured under different loading conditions. Since this is a propeller the load torque is proportional to the square of the speed (Fig. 6).

The measured temperatures are presented in Fig. 7.

Fig. 6 Plot of load curve

V. COMPARISON OF MEASUREMENTS AND CALCULATION

Fig. 8 presents a comparison of the measured and the calculated curves for the actual loading condition (presented in Fig. 6).

Fig. 7 Plot of measured temperatures

Fig. 8 Comparison of calculated and measured temperature with only copper and iron losses (20 K/div)

From the curves (Fig. 8) it can be seen that there are some deviation, both in shape and amplitude, but the deviation is fairly small and acceptable within the area of operation. It is the curve with thermal insulation equal to 0.20 that best resemble the measured curve best.

The measurements were done during sea trials of the thruster on the fjord outside Molde with relatively controllable surroundings. This means that weather and wind can have affected the measurements. Some of the measurements were done over such a short time so that steady state might not have been reached. Especially with high load this can be critical, and one can expect that the measured curve would have been somewhat steeper had sufficient time been used to measure the temperature. The temperature is also measured to few places to give an exact picture of the temperature rise in the machine. And of course there is also the question about the accuracy of the measurements.
The conclusion of the calculations and measurements is therefore that the model gives sufficient results to show both the trend and the amplitude of the temperature at different loads within the area of operation. To further nail the different thermal transition resistances and resistance in the coil insulation, more tests and measurements will be done.

VI. REFERENCES

(http://www.brunvoll.no/Web/webPublisher.nsf/0/6AEA41A870B1106BC125707A002EA46C?Open Document)
VII. APPENDIX

A. Thermal Network

Fig. 9 Slot and tooth

Fig. 10 The coil