

Chapter 7

Model evaluation

In this chapter, the thermal model developed in chapters 3 - 6 is used to predict the thermal distribution of the TWINS at rated speed and load. A sensitivity analysis is used to investigate the influence of some parameters on the temperatures inside the machine. Reduction in the machine's temperatures can also be achieved by reducing the interface resistances. The rotor eddy current loss is discussed and ways to reduce it, presented.

7.1 Model temperatures at 30000 r/min

The thermal model for the TWINS can be used to predict the temperatures when operating at 30000 r/min. The losses that are expected when operating at full load (4 kW) are summarized in Table 7.1. The motor efficiency is predicted to be more than 95 %. The tangential current width determined from the switched test ($w_t = 11$ mm) is used to determine the rotor eddy current loss. Being the largest single loss component on the rotor makes it very important. The bearing loss is assumed to be three times the bearing loss determined through the no-load test done at 10000 r/min since bearing loss is directly proportional to the rotation speed (see (5.21)).

Figure 7.1 shows the predicted temperatures above ambient. As expected, the highest temperature rise is in the PM, which is predicted to have a temperature around 400 K (130 °C) if the ambient temperature is 293 K (20 °C). According to the mechanical stress analysis, the rotor cannot be safely operated at 30000 r/min if the PM temperature is higher than 80 °C [16]. As the PM temperature increases, it will lose contact with the rotor laminations which could result in mechanical failure of the rotor. Figure 1.1 shows the effect of temperature on the PM material (VACODYM® 655). A temperature change from 20 °C to 150 °C causes a decrease in remanence from 1.26 T to 1.098 T. The coercivity reduces from 960 kA/m to 654 kA/m and the maximum energy density from 307 kJ/m³ to 217 kJ/m³. The knee of the demagnetization curve also shifts, making it easier to permanently reduce the remanence or demagnetize the PM. Remagnetization of the PM is the only way the original operating point can be regained after demagnetization. This type of demagnetization is due to magnetic loading. The Curie temperature of VACODYM® 655 is between 310 °C and 370 °C, where the PM is demagnetized

Table 7.1: Expected losses in the TWINS at 30000 r/min and 4 kW output power in motor mode with a VSI

Location	Type	Loss [W]
Stator laminations	Eddy currents and hysteresis	8.62
Winding	Eddy currents	18
Winding	Conduction	19
End Winding	Conduction	38
Bearing	Friction	81
Rotor surface	Friction	1.93
Shielding cylinder and PM	Eddy current	41.8
	Total	208.35

due to heat.

The reduced remanence at high temperature will result in a smaller back emf in the PMSM. The maximum torque will also reduce, thus the machine will more easily lose synchronization at high loads or a sudden change in load. This can be improved through control and including PM temperature in the machine control should be investigated.

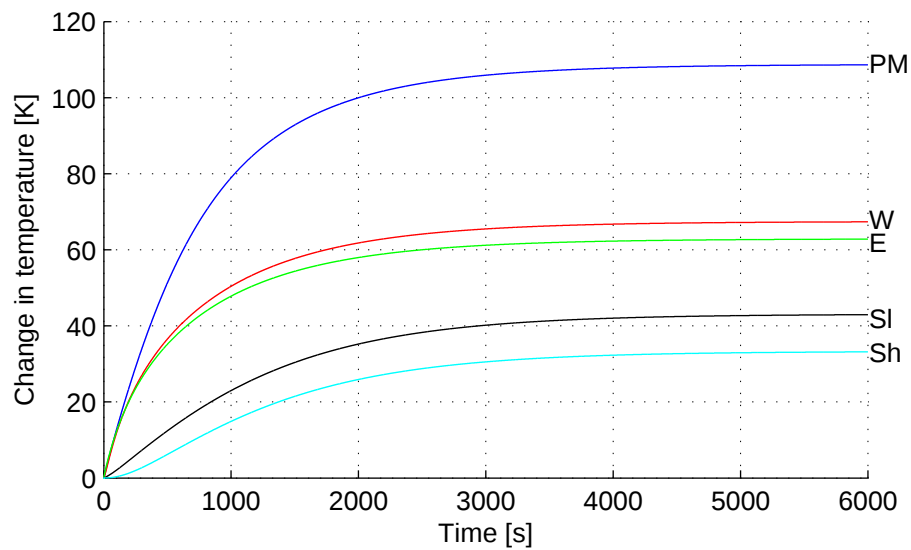


Figure 7.1: Predicted TWINS temperatures at 30000 r/min, 4 kW output, motor mode with VSI

7.1.1 PM temperature distribution

The distributed model developed in chapter 4 can be used to determine the temperature distribution of the PM. Through this model it can be shown where demagnetization is most likely and what portion of the heat flows in the radial and axial directions. The input parameters required for the distributed model are the convection coefficients in the air gap (h_b) and end space (h), as well as the loss in the shielding cylinder (q_{loss}) and the heat flowing into the rotor (q_{PMi}). These are calculated for the TWINS operating at 30000 r/min next.

Calculation of the convection coefficients

The Reynolds number in the air gap was calculated as 3252 in section 5.6.2. The Taylor number gives an indication of the type of flow and can be calculated using (2.14):

$$\begin{aligned} \text{Ta} &= \text{Re} \sqrt{\frac{L_g}{r_r}} \\ &= 3252 \sqrt{\frac{0.5 \times 10^{-3}}{31.5 \times 10^{-3}}} \\ &= 409. \end{aligned} \quad (7.1)$$

Turbulent fluid flow is expected in the air gap since $\text{Ta} > 100$, thus (2.15c) should be used to calculate the Nusselt number:

$$\begin{aligned} \text{Nu} &= 0.386 \text{Ta}^{0.5} \text{Pr}^{0.27} \\ &= 0.386 (409)^{0.5} (0.73)^{0.27} \\ &= 7.17. \end{aligned} \quad (7.2)$$

The convection coefficient in the air gap can be calculated using (2.9):

$$\begin{aligned} h_b &= \frac{\text{Nu} k}{L} \\ &= \frac{(7.17)(0.025)}{0.5 \times 10^{-3}} \\ &= 358. \end{aligned} \quad (7.3)$$

Convection heat flow is proportional to the convection coefficient and the difference between the surface and fluid temperatures. The thermal resistance in the air gap will be small and a small thermal drop is expected across the air gap.

The sides of the PM can be modelled as a disc rotating in a large air space. The Reynolds

number can be calculated using [135]:

$$\begin{aligned}
 \text{Re} &= \frac{\rho \omega r_r^2}{\mu} \\
 &= \frac{(1.2)(2\pi 500)(31.5 \times 10^{-3})^2}{18.25 \times 10^{-6}} \\
 &= 2.07 \times 10^5,
 \end{aligned} \tag{7.4}$$

which is smaller than 3×10^5 , above which turbulent flow starts to develop [136]. The Grashoff number can be calculated using:

$$\begin{aligned}
 \text{Gr} &= \frac{g \beta r_r^3 \pi^{3/2} \Delta T}{\nu^2} \\
 &= \frac{(9.8)(1/333)(31.5 \times 10^{-3})^3 \pi^{3/2} (80)}{(15 \times 10^{-6})^2} \\
 &= 1.85 \times 10^6.
 \end{aligned} \tag{7.5}$$

The Nusselt number can be calculated using:

$$\begin{aligned}
 \text{Nu} &= \frac{2}{5} (\text{Re}^2 + \text{Gr})^{1/4} \\
 &= \frac{2}{5} ((2.07 \times 10^5)^2 + 1.85 \times 10^6)^{1/4} \\
 &= 182.
 \end{aligned} \tag{7.6}$$

The convection coefficient on the side of the PM is:

$$\begin{aligned}
 h &= \frac{\text{Nu} k}{L} \\
 &= \frac{(182)(0.025)}{31.5 \times 10^{-3}} \\
 &= 144.
 \end{aligned} \tag{7.7}$$

The convection coefficient in the z - direction (h) is much smaller than in the r - direction (h_b). This is expected since turbulent flow exists in the air gap and laminar or vortex flow exists in the end space area.

Predicted temperature distribution

Figure 7.2 shows the PM temperature distribution, calculated using the calculated convection coefficients and losses. Note that the ambient temperature needs to be added to attain the absolute temperature. The radial heat flux is the largest since the convection coefficient in this direction is 2 times larger than in the axial direction. The surface area is also 4 times larger in the radial direction than in the axial direction. According to the 2-D distributed model, only 0.4 W flows through each of the sides (axial direction) and 14.6 W into the air gap (radial direction). The ambient temperature inside the machine could not be measured, thus the 2-D distributed

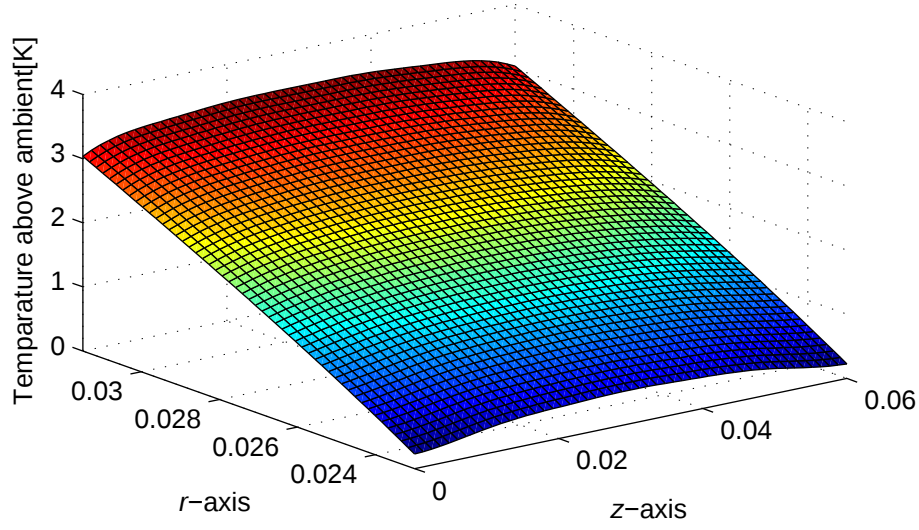


Figure 7.2: Predicted PM temperature distribution of the TWINS at 30000 r/min at full load

model cannot be verified using the experimental results. A thermal camera can be used to get a better idea of the side temperature distribution. Measuring the air gap temperature or rotor radial outside temperature is very difficult and has not been encountered in literature.

During the derivation of the 2-D model, assumptions were made in terms of the ambient temperature and loss location. It was assumed that the ambient temperature is the same in the radial and axial outside surfaces of the rotor. This assumption made it possible to use a linear transformation, thus allowing the use of the SOV method to solve the diffusion equation as documented in section 4.2.1. Heat is generated in the winding and rotor, thus it is expected that the air gap temperature will be higher than the end space temperature. If this is the case, the axial heat flow would be significant since the convection heat flux is directly proportional to the temperature difference between the surface and fluid. CFD could be used to investigate the fluid temperature and movement inside the machine but the turbulent flow inside the air gap will pose significant challenges. In the next paragraph this will be investigated qualitatively.

Predicted temperature distribution including air gap temperature

The LP model can be used to analyse the effect of the inside air temperature on the PM temperature distribution. The goal is to illustrate the influence of under estimating the air gap temperature, rather than finding the exact PM temperature distribution. This section qualitatively investigates the effect of the air gap temperature since the machine inner air was not modelled and could not be measured. According to the LP model, the difference between the air gap temperature and the PM temperature is only 2.88 K. The difference between the end winding temperature and the PM temperature is 46.78 K, on the other hand. The convection heat flow is directly proportional to the convection coefficient and the temperature difference, as shown in:

$$q_{conv} = hA(T_s - T_{\infty}). \quad (7.8)$$

Thus the convection coefficient can be reduced by the same percentage that the temperature differs to explore the effect that the high air gap temperature has on the PM temperature distribution. Different convection coefficients were used in the axial and radial directions, as shown in (4.23) and (4.25). Figure 7.3 shows the predicted PM temperature when the convection coefficient is 6 % of the calculated value, thus accounting for the high air gap temperature.

Figures 7.2 and 7.3 are compared to investigate the effect of the higher air gap temperature on the shape and value of the PM thermal distribution. The PM temperature is at least 20 K higher when accounting for the higher air gap temperature since less heat flows through the air gap area. According to the distributed model, 6.544 W flows into the air gap compared to the 14.6 W previously presented. Consequently, the total heat flow in the z - direction increases from 0.4 W to 8.44 W. The heat flow is much more two dimensional when accounting for higher air gap temperature. The hot spot in the PM is also more pronounced and this could cause local demagnetization in extreme cases. The 2-D analytical distributed model will be very helpful in predicting the PM temperature distribution if the inside air temperature distribution is known. Note that the machine temperatures presented previously are all based on the worst case scenario; where most of the heat flows in the radial direction. A sensitivity analysis can be used to explore the effect selected parameters have on the machine temperature.

7.2 Sensitivity analysis

Even though the model derivation and refinement were extensive, there are always uncertainties during this process. A sensitivity analysis is done to determine which parameters have the largest influence on the crucial part of the PMSM, the PM.

Most of the thermal resistances and capacitances were determined from the geometry and ma-

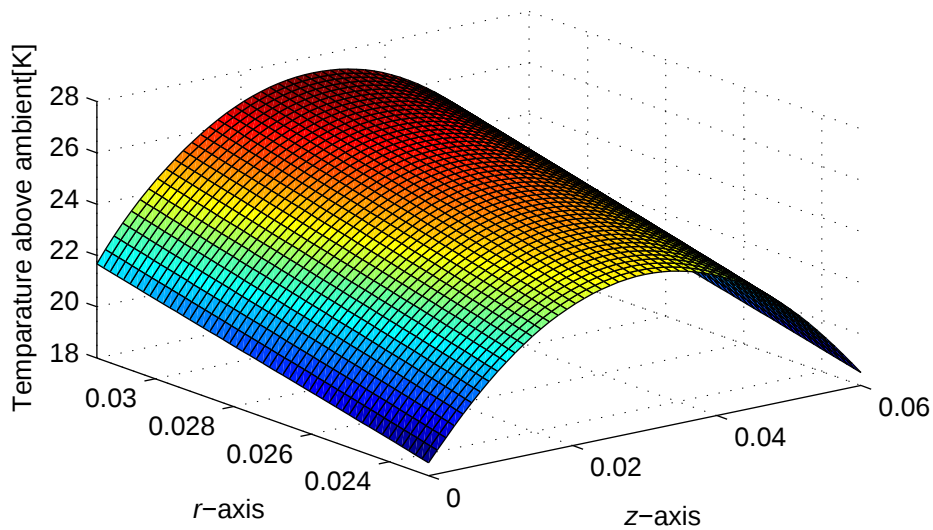


Figure 7.3: Predicted PM temperature distribution of the TWINS when taking into account the air gap temperature.

terial data of the TWINS. The thermal capacitances only influence the transient behaviour and is not taken into account in this section. Ultimately, the highest (steady state) temperatures are the most important when predicting machine integrity during long operating periods.

Table 7.2 shows the change in temperature when the interface resistance and convection resistance values are decreased and increased by 50 % from the values determined in chapter 6. The influence that one thermal resistance has on the various machine temperatures can be seen from this sensitivity analysis. In each case, the temperature above ambient (ΔT) and temperature above ambient with the change in the parameter (ΔT^*) is used to determine the percentage change:

$$\% \text{ change} = \frac{\Delta T - \Delta T^*}{\Delta T} \times 100\% \quad (7.9)$$

Table 7.2: Sensitivity analysis: Temperature variation due to thermal interface resistance variation

		Percentage change in temperature				
Resistance	% change	T_{PM}	T_W	T_E	T_{SI}	T_{Sh}
R_{rSI}	-50	-0.59	-1.39	-1.17	-6.21	5.68
	+50	0.5	1.25	1.05	5.58	-5.11
R_{rC2I}	-50	-0.73	-1.73	-1.455	7.07	7.09
	+50	0.61	1.45	1.21	-5.92	-5.93
R_{rC1I}	-50	-6.12	1	0.4	0.3	0.3
	+50	4.27	-0.7	-0.3	-0.21	-0.21
R_{rRI}	-50	-7.59	-0.85	-0.35	-0.23	-0.23
	+50	6.2	0.69	0.28	0.19	0.18
$R_{nat,conv}$	-50	-2.2911	-5.4918	-4.5978	-24.5779	-38.4983
	+50	1.5007	3.6560	3.0555	16.4948	25.9175
$R_{for,conv}$	-50	-24.7866	-37.3475	-42.0477	-34.1191	-34.0885
	+50	21.8293	32.9688	37.1502	29.9308	29.8346

The interface resistances closest to the PM, R_{rC1I} and R_{rRI} have the largest effect on the PM temperature. This is expected since these interfaces are located in the main heat flow paths from the PM. The winding and end winding are cooled through the forced convection, thus the changes in these interface resistances do not have a large influence on the PM temperature. The interface resistance at the stator lamination and stator housing (R_{rSI} , R_{rC2I}) has a large

effect on the temperatures in the neighboring components (T_{Sl} , T_{Sh}). The interface resistances are discussed in more detail in section 7.3. The machine temperatures are most sensitive for the cooling resistances ($R_{nat,conv}$, $R_{for,conv}$), especially the forced convection since most of the heat is removed through it. It is clear that the largest part of the PM heat is removed through the forced convection since this temperature is more sensitive for a change in $R_{for,conv}$ than a change in $R_{nat,conv}$.

Table 7.3 shows the sensitivity of the machine temperatures due to variation in the losses. The PM temperature is influenced the most by the shielding cylinder loss and bearing loss. Reduction of the rotor eddy current loss is discussed in more detail in section 7.4. These are also the two largest losses and are both located close to the PM. The bearing loss is the largest single loss component and a change in it has a large influence in all parts of the machine. The bearing loss is discussed in more detail in section 7.5.

Due to the large influence of the interface resistances and rotor eddy current loss on the PM temperature, these are discussed in more detail in the following sections.

7.3 Interface resistance reduction

The temperature inside the machine can be reduced by reducing the interface resistance.

Table 7.3: Sensitivity analysis: Temperature variation due to loss variation

		Percentage change in temperature				
Loss	% change	T_{PM}	T_W	T_E	T_{Sl}	T_{Sh}
Shielding cylinder	-50	-27.2509	-11.2423	-10.8633	-8.6978	-8.6933
	+50	27.2508	11.2423	10.8634	8.6979	8.6931
Winding	-50	-5.8705	-11.6048	-9.7914	-10.7721	-10.7735
	+50	5.8704	11.6048	9.7915	10.7722	10.7733
End winding	-50	-5.4468	-9.3774	-9.8021	-8.6488	-8.6494
	+50	5.4467	9.3774	9.8022	8.6489	8.6493
Stator laminations	-50	-0.6809	-1.6101	-1.3498	-7.0785	-7.0814
	+50	0.6808	1.6101	1.3499	7.0786	7.0813
Bearing	-50	-10.7512	-16.1654	-18.1932	-14.8025	-14.8027
	+50	10.7511	16.1654	18.1933	14.8026	14.8026

7.3.1 Factors influencing interface resistance

As discussed in section 2.5, the thermal interface resistances are influenced by surface roughness, interface pressure, hardness and the material filling the voids in the interface.

Average surface roughness is influenced by the manufacturing technique used which in turn influences the manufacturing cost. A smoother surface usually costs more to manufacture but should be considered when the interface resistance must be minimized. Common tolerance and surface roughness of turning/boring with a lathe is 25 - 57 μm and 0.8 μm , respectively [137]. An average roughness height of 0.05 μm is possible with superfinishing but costs up to 4 times more than milling [138]. Tolerances are also very important when a part must be fitted into another part since the interface pressure is directly dependent on the type of fit.

During the machine design stage, interface resistance should be calculated using the manufacturing technique's surface roughness and required fits. The surface roughness is influenced by the machines used, tool sharpness and operator skill, to name a few. Before approving components, the specified surface finish and dimensions should be measured to ensure the design specifications have been met. In extreme cases, the interface resistance should be measured when assembling the machine. This will ensure that all interfaces are within design tolerances and at that stage it can easily be addressed if not. Determining the interface resistances once the machine is completely assembled might be easier since the windings can be used as a heat source, but modifications are then more difficult and costly.

7.3.2 Influence of interface resistances on the TWINS

Using the thermal model, the influence of the various interface resistances on the PM temperature can be investigated. Figure 7.4 shows the PM temperatures when all the interface resistances are as derived during Chapter 6 as well as the temperature reduction when replacing the interface resistances with short circuits. Replacing the interface resistance with a short circuit removes the temperature difference across it, thus modelling a perfect interface. The highest temperature is when all the interface resistances are in place. Removing R_{rSI} gives the second highest temperature, removing R_{rC21} the third highest, etc.

The different effect each of the interface resistances has on the PM temperature is influenced by the forced convection cooling location. The resistances R_{rSI} and R_{rC21} are not located in the main heat removal paths of the PM but R_{rC1I} and R_{rRI} , are. Even though the coil former material is a better thermal conductor than air, the turbulent flow in the air gap reduces the thermal resistance. That is why reducing the thermal resistance between the PM and winding will decrease the temperature of the PM significantly. The PM heat also flows through the rotor and bearings to the stator housing. Reducing the interface resistance between the PM and rotor laminations thus also significantly reduces the PM temperature.

The next few paragraphs discuss the mechanisms causing the interface resistances in the TWINS. Some suggestions to reduce the interface resistances in the TWINS and electric machines in general, are given.

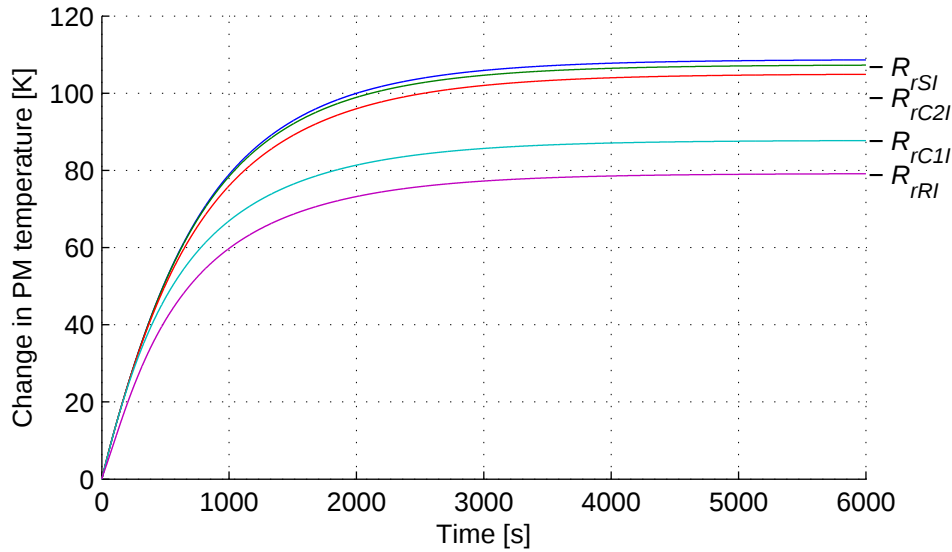


Figure 7.4: Modelled influence of the interface resistances on the PM temperature at 30000 r/min, full load.

7.3.3 Stator housing and stator lamination interface

The manufacturing techniques used for the TWINS are directly related to the interface resistances. The stator laminations were punched from a sheet of electric steel. The difference in size between the laminations are significant, with a tolerance of up to 0.12 mm measured on the circularity. The laminations were stacked inside the stator housing and a loose fit exists between these two parts. The inside of the stator housing was bored using a lathe and no additional surface finishing was done. This manufacturing technique results in a large interface resistance. The use of forced convection to cool the end winding reduces the influence of this interface on the machine temperature. Most electric machines are however totally enclosed, keeping impurities that can damage the bearings and rotor out of the machine. All the heat must be removed through the stator housing in this case.

A shrink or press fit should be used between the stator laminations and stator housing. Both surfaces should be machined. If the material hardness of the two parts are similar, the surface roughness of both should be as small as possible. Alternatively, a softer metal with good thermal conductivity can be placed in the interface. This material will be remodelled by the forces, causing a good thermal interface. The influence of mechanical pressure on the magnetic properties of the laminations must be taken into account when deciding on the fit type.

7.3.4 Coil former and stator winding interface

In a slotless stator, the coils are not inserted into and kept in place by the stator laminations like when a slotted stator design is used. A tufnol coil former was used to keep the coils in place and is shown in appendix B, Figure B.5. To ensure mechanical integrity of the coil former, a uniform width of 1 mm is used. From a thermal point of view, the coil former only adds to

the thermal resistance. It also reduces the space available for the winding and increases the effective magnetic air gap.

The stator winding is vacuum impregnated with resin. This increases the thermal conductivity, increases the electrical insulation and increases the winding's rigidity. The latter reduces vibrations that can cause audible noise and destroy the insulation of the winding. Since the resin is baked and hardened to a solid, the inner sleeve of the coil former does not contribute to the containment of the winding after vacuum impregnation. This part can thus be designed to be removed after vacuum impregnation. In the TWINS, this would result in a 12.5 % increase in winding area or a reduction of 1 mm in magnetic air gap. Methods to decrease the outside sleeve width of the coil former should also be investigated. A winding jig that is used to form the coils, but not inserted in the stator laminations, could be used. The use of a needle-and-thread winding approach should be avoided since it is an extremely time consuming process. Unbalance in phase resistance and inductance, as seen in Table 6.2, is also a result of this manufacturing technique. The use of resin with high thermal conductivity should also be investigated [139].

7.3.5 Rotor interfaces

The interface between the shielding cylinder and PM is very good due to the high interface pressure. A 125 μm interference fit was established by heating the shielding cylinder to 300 °C and pressing it over the PM. The Curie temperature of the VACODYM magnets used in this project is 315 °C, thus this did not cause demagnetization. The large surface and small volume of the shielding cylinder caused rapid cooling during assembly. This was needed to ensure the PM is not damaged due to centrifugal forces at high speed.

The interface between the PM and rotor laminations is not very good from a thermal point of view. A sliding fit was used at this interface and the PM was fixed to the rotor laminations using glue. The shaft and rotor laminations interface was realised by a shrink fit, thus the interface resistance is small here.

If a sliding fit is required between the rotor laminations and PM, the glue should be impregnated with a good thermally conducting material. Aluminum oxide is a good candidate due to its high conductivity, 40 W/(m.K) and powder form. Other non-metallic substances, like silicon carbide should also be investigated for use in glue and resin.

The machine temperature can be reduced by reducing the interface resistances, increasing the cooling or reducing the loss inside the machine. The former is discussed for eddy current loss in the next section.

7.4 Rotor eddy current reduction

It is clear that eddy current loss in the rotor is a significant problem in high speed PMSMs. This section will discuss some of the approaches that can be taken to address this problem.

7.4.1 Reduction of the harmonic stator currents

The eddy current loss is proportional to the square of the current, thus reducing the high frequency currents will significantly reduce the eddy current loss. A filter could be used between the VSI and machine to attenuate the high frequency currents. The filter should be designed to have minimum losses since the power losses in the filter must be supplied by the drive, thus influencing the overall efficiency. The main advantage of an external filter is reducing heat generation on the rotor. Rotor heat can damage the PMSM and is difficult to remove. It can more easily be removed from an external filter. The influence of the filter on the dynamic behaviour of the machine should also be taken into account during its design.

7.4.2 Reduction of the eddy current loss in the tangential direction

It is clear from Figure 5.12 that the eddy current loss in the ϕ - direction is significantly higher than in the z - direction. This can be attributed to the rotor geometry, the materials used and the switching frequency. The eddy current loss is directly proportional to the resistance. The resistance in the ϕ - direction can be reduced by increasing the current direction changing area or using a material with a lower resistivity in the end space. The properties of materials that will be good candidates are given in Table 7.4 as well as that of the current shielding cylinder material (INCONEL[®] 718). INCONEL[®] 718 were chosen because of its very high yield strength, required to keep the PM from losing contact with the laminations due to centrifugal force at 30000 r/min [16]. Using any of the other materials will decrease the resistance significantly and thus reduce the eddy current loss by an order of magnitude.

Placing a ring, made from a good conductor like those listed in Table 7.4, will be a good solution to the eddy current loss in the ϕ - direction but this solution has additional challenges. One of the challenges is ensuring good contact between the shielding cylinder and end ring. A shrink fit or electroplating could be used. Force calculations on the end ring is crucial since most good conductors have a high density and a low yield strength. A material with a high density will experience a larger centrifugal force than one with a lower density due to the increase in weight. In order to prevent large hysteresis loss on the rotor and limit leakage flux, the end ring should be made from a non-magnetic material.

Table 7.4: Shielding cylinder materials

Material	Resistivity [$\Omega\cdot\text{m}$]	Density [kg/m^3]	Yield strength [MPa]
INCONEL [®] 718	1.7×10^{-6}	7391	1100
Annealed Copper	17.2×10^{-9}	8890	210
Aluminium	26.17×10^{-9}	2702	400
Silver	16.2×10^{-9}	10500	124

7.4.3 Reduction of eddy current loss in the axial direction

If maximum efficiency needs to be achieved, the eddy current loss in the z - direction should also be minimized. The required thickness of the shielding cylinder is material dependent since the penetration depth of a conductor is proportional to the square root of the resistivity. If a 50 kHz switching frequency is used in the VSI, a copper shielding cylinder would only need to be 0.3 mm thick. This creates the opportunity for implementing shielding cylinders manufactured from more than one material. If the copper can withstand the centrifugal forces, the $P_{z,e}$ can be reduced by ten times in the TWINS by electroplating 0.3 mm copper over the current INCONEL[®] 718 sleeve.

Another option would be to manufacture a shielding cylinder using carbon fibre and silver or copper. A layer of conducting material can be placed on the OD of the PM and then carbon fibre is wound around it. The conductor provides the magnetic shielding and the carbon fibre ensures mechanical integrity. The use of carbon fibre was investigated during manufacturing of the TWINS but no local manufacturers were found that could manufacture a pretensioned carbon fibre shielding cylinder [16].

A prefabricated carbon sleeve can also be used but establishing the interference fit is crucial. One way of doing this is cooling the rotor using liquid nitrogen and then sliding the sleeve over it. Another is axial pressing of the sleeve using a hydraulic press. The latter was found to damage some of the inner fibres, thus the former is the preferred choice [140]. Carbon fibre can handle large forces in the parallel direction but is fragile to bending or perpendicular forces. Binder *et al.* used a thin layer of glass fibre between the PMs and carbon fibre sleeve to decrease bending forces on the carbon fibre sleeve. Expansion due to temperature change is also very important when designing the containment system. From stress analyses it is shown that the safety factor of the TWINS' rotor degrades to 1.7 when the rotor is at 80 °C [16], thus this is the limiting rotor temperature at 30000 r/min.

7.4.4 Predicted machine temperature when using a copper shielding cylinder

The thermal model presented in section 6.8 can be used to determine the influence of the shielding material on the machine temperatures. Figure 7.5 shows the predicted machine temperatures when copper is used as shielding cylinder material. The reduction in shielding cylinder loss can clearly be seen. If the machine is operated where the ambient temperature is 293 K (20 °C), the PM temperature is expected to be below 80 °C. As stated earlier, the machine will then be able to operate at rated speed and load without PM failure.

7.5 Bearing loss reduction

A large discrepancy exists between the theoretical bearing loss calculated in section 5.6.1 and the loss found from the no-load test. The mechanical design of the bearing containment makes axial loading possible since the bearing is restricted in the axial direction. Figures B.2 and B.7

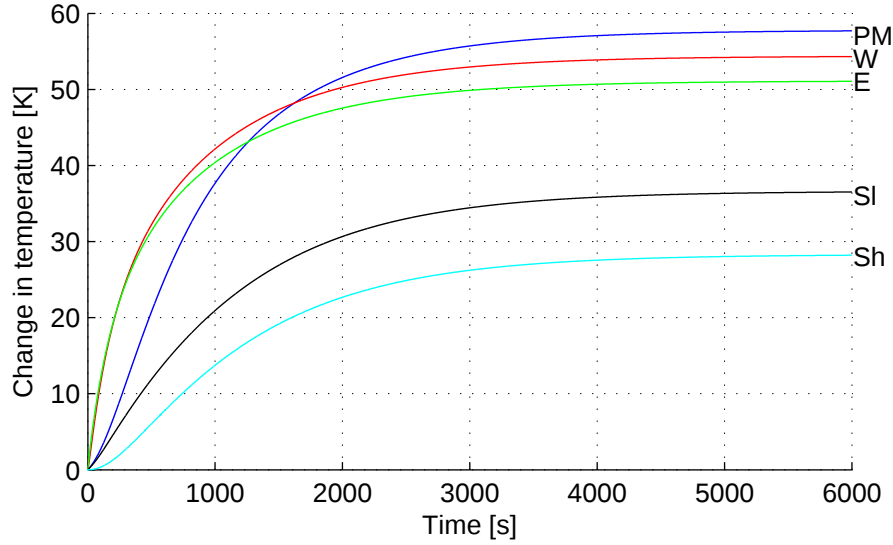


Figure 7.5: Predicted temperatures when a copper shielding cylinder is used

in appendix B shows a 2 mm lip which restricts the bearing from moving in the axial direction. This means that the bearing can be axially loaded during assembly as well as during operation due to thermal expansion. This problem can be remedied by removing this lip, but there are still many unknowns surrounding the bearing. The forces acting on the bearing as well as the friction coefficient of hybrid bearings are unknown. The higher than expected bearing loss is thought to be due to manufacturing issues but a thorough investigation of the bearing loss should be performed.

7.6 Conclusion

The thermal model was used to calculate the expected temperatures at 30000 r/min and it was found that the PM temperature will be higher than 400 K (130 °C) if the ambient temperature is 293 K (20 °C). According to the mechanical stress analysis the machine will thus not be able to operate at rated speed and load for extensive time periods [16].

The distributed model was used to predict the PM temperature distribution but could not be verified since the inside air temperature could not be measured. A qualitative comparison was presented when using an air gap temperature predicated through the thermal model. If the air gap temperature is higher than the end space temperature, more heat will flow from the PM in the axial direction.

It was shown through a sensitivity analysis that the PM temperature is most sensitive to R_{rC1I} , R_{rRI} , $R_{for,conv}$, shielding cylinder loss and bearing loss. The first two is located closest to the PM and inside the main heat flow paths. The entire machine is sensitive to the forced convection resistance since most of the heat is removed through this cooling mechanism. The shielding cylinder loss and bearing loss are the largest loss components on the rotor and in the entire machine, respectively.

The interface resistances were discussed for the TWINS machine as well as methods to decrease them. The rotor eddy current loss was also discussed in detail.

