

Chapter 8

Conclusions and recommendations

8.1 Conclusions

The focus of this thesis was the development and verification of an analytical thermal model for a high speed PMSM. The PMs are thermally the most fragile part of a PMSM and it was shown from literature that this part of the machine must at least be modelled in 2-D. A LP model was used to determine the heat flow in the PM due to the entire machine's thermal distribution. The solution time and model complexity of the LP model makes it well suited for thermal modelling of electric machines. The LP model predicts the average temperature in a component and is thus unsuited to predict the PM temperature distribution. A 2-D analytical distributed model was derived to overcome this problem in the LP model and is one of the main contributions of this thesis.

Losses are an important and integral part of thermal modelling since they are the heat flux sources in an electric machine. The eddy current loss on the rotor can only be accurately determined through a 3-D distributed model but in this thesis it was derived empirically. A simple 1-D lumped model was used to analyse the rotor eddy current loss and to calculate the expected loss at rated speed and load. Various ways for minimizing the rotor eddy current loss were discussed. It was shown that a copper shielding cylinder would decrease the rotor eddy current loss and PM temperature in the TWINS to within operating limits. It is predicted that the TWINS will not be able to operate at rated speed and load with the current INCONEL[®] shielding cylinder.

Five tests were performed to determine the interface and convection resistances and to explore the losses found in a high speed slotless PMSM systematically. It was found that the bearing loss in the TWINS was much higher than expected during no-load tests at 10000 r/min. A significant difference in the interface resistances determined during the DC test and no-load test was found. It seems that using only a DC test to determine the interface resistances is not sufficient in the case of a high speed PMSM. The distributed nature of the losses makes using additional tests, like the no-load test, necessary during model derivation. It was also found that the forced convection cooling of the end windings is an efficient way of cooling the machine.

The distributed model was verified using a 2-D FEM model, implemented in COMSOL Multiphysics 4[®] and a good correlation was found. Since the combined model was refined through experiments, it was not verified. This model was used to predict the temperature in the machine at 30000 r/min and a sensitivity analysis was used to investigate the influence of various parameters on the machine's temperatures.

8.2 Unique contributions

The three main contributions of this thesis are:

Distributed thermal model: Distributed thermal models have been solved using analytical methods for decades. Deriving a 2-D analytical distributed thermal model of the PMs located on the rotor of the PMSM, with convection boundary conditions used on three of the boundaries and a constant heat flow on the fourth, has not been found in literature. The model was verified using FEM and showed good correlation even for a small number of summations of the series expansion used. It was found during loss calculation that the eddy current loss was not limited to the shielding cylinder as assumed in the derivation of the distributed model. This is due to the high resistivity of the shielding cylinder material. A shielding cylinder should be made from a highly conductive material and be thick enough to ensure the eddy currents flow only in the shielding cylinder. The model could not be validated through experimental data since the fluid temperature in the air gap and end space could not be measured. These were needed to determine the absolute temperature of the PM. It was also assumed during the model derivation that the fluid temperatures in the air gap and end space are equal in order to reduce the diffusion equation to a homogeneous Laplace equation. If this is not the case, axial heat flow will become significant.

Hybrid thermal model: LP thermal models are commonly used in electric machines due to the simplicity and rapid solution of this method. The limitation of the LP model is that only the average component temperature is determined. FEM is mostly used if the thermal distribution must be determined in higher resolution. In this thesis, the distributed analytical model was used in conjunction with the LP model, something that has not been seen in literature.

Experimental investigation: PM containment is an important part of high speed PMSMs' mechanical and electromagnetic design. High centrifugal forces acting on the PM can damage it and thus cause a critical failure. The containment cylinder of the TWINS is manufactured from INCONEL[®] because of its very high yield strength. Unfortunately, the resistivity of INCONEL[®] is much higher than preferred shielding cylinder materials like copper. This results in high eddy current loss on the rotor, worsened by the high frequency switching in the VSI. The systematic experimental investigation of the loss components found in a high speed slotless PMSM has not been seen in literature. It was shown that the shielding cylinder loss is a large part of the total rotor loss. Novel suggestions on reducing eddy current loss in the rotor were discussed.

8.3 Recommendations for future work

This thesis only scratched the surface of what could be the Achilles heel of high speed electrical machines: thermal integrity. Some issues that should still be addressed are listed in this section.

8.3.1 Thermal modelling

Analytical distributed models yield the greatest rewards when used for optimization during design. Creating an analytical, coupled thermal and electromagnetic model will be a significant contribution. Such a coupled model can then be used to design an optimal machine in both domains simultaneously. The influence of the losses on the material properties (e.g. resistivity) will then be taken into account, resulting in the optimum design in terms of efficiency, manufacturing cost, etc. Including the reduction in PM remanence and coercivity due to increased heat could enable the designer to use the optimal amount of magnetic material, thus ensuring reliable operation and reducing machine costs.

To verify the distributed PM model, the inner fluid temperature of the machine must be determined. The flow inside a high speed machine is very complex and advanced methods like CFD could be used to model the heat and mass flow. Advanced cooling methods, like forced cooling in the air gap through rotor mounted or external blowers should be investigated.

The methods described in sections 7.3 and 7.4 should be considered before operating the TWINS at high speed for extensive periods. The predicted rotor loss should also be verified experimentally.

8.3.2 Measuring

Accurate temperature measurement remains difficult. In most cases, the sensor influences the thermal distribution, e.g. the RTDs used in the TWINS to measure the winding temperature. These sensors have a finite size (1 mm diameter), thus influencing the winding distribution when placed inside the winding. Temperature measurement of the rotor is also difficult, especially when rotating at high speeds. The IR sensor used in the TWINS gives the average temperature on the side of the rotor but the temperature in the air gap could not be measured. Hot spots cannot be found using this type of sensor. The use of a thermal camera should also be explored.

Measuring rotor temperatures with RTDs is difficult since the signals are usually connected to measuring equipment through slip rings. This results in excessive noise, corrupting measurement data. With advances in wireless data transfer, this should be investigated to get the data from the rotor. Digitizing the measurements on the rotor will limit the effect of noise when sending the measurements from the rotor to the stationary data logger. Since thermal time constants are much slower than wireless data rates, the same measurements can be resent multiple times. This will add reliability to the data. Alternatively, the data can be stored on the rotor using flash or RAM memory. Other measurements like torque and vibration can also be mea-

sured using such a platform. Torque measurement in high speed machines is difficult because it is very small compared to low speed machines. Vibration sensors mounted inside the rotor could be used to shed some light on the rotor dynamics of a complex, layered rotor used in high speed machines.

8.3.3 Manufacturing

It was shown that forced cooling of the end winding is a very good way of removing heat from the machine. The use of resin with a high thermal conductivity should be investigated if a totally enclosed design is required. In most industrial machines the end windings are surrounded by air, thus only contributing to loss inside the machine and not utilized as a heat removal path. By filling end winding areas with highly thermally conductive resin, this heat removal path can also be utilized.

Even though thermal design is considered part of the mechanical engineer's domain, machine designers must promote good thermal design. There should be a constant dialog between the designers of the mechanical and magnetic parts of a machine to ensure the thermal interfaces are kept as small as possible.

8.4 Closure

This thesis developed and verified an analytical thermal model for a high speed PMSM. A LP model and analytical distributed 2-D model were combined into a hybrid model. The PM thermal distribution due to the heat flow in the entire machine can be predicted using this model. Many experiments were used to refine the model and investigate the main loss components of a high speed PMSM. In the TWINS, these were the rotor eddy current loss and bearing loss. It was also found that the inside air temperature distribution is needed in order to accurately determine the PM temperature distribution. These issues should be addressed in future research. This thesis illustrates the importance of thermal modelling as an integral part of electric machine design.