

Chapter 1

Introduction

In this first chapter, the objective is to identify and formulate an original research problem relating to thermal modelling of high speed electric machines. Global trends on this subject is explored and the test platform is introduced. From this, the research problem is formulated and the research methodology is discussed. The envisioned contributions are given as well as a layout of the rest of the document.

1.1 Global trends

Electric machines form an integral part of modern society. Applications include generating electrical power, pumping water, transporting people and goods in trains, buses, boats and even motorcars. These devices are manufactured in sizes ranging from a few nanometers to several meters. Over the centuries, electric machines have been improved in terms of power density, effectivity, speed range and cost. Machines that do not require an electrical link between the power supply and the rotor (brushless) have become the preferred choice. These machines have longer service intervals and lower running costs than machines with brushes. The induction motor is widely used because of its rugged construction and brushless operation.

Profit is the main objective of modern business and one of the important ways of increasing profit is by reducing costs. This justifies designing electric machines with higher efficiency which is manufactured from less material. The former results in a lower running cost and the latter in a lower manufacturing cost. Even though this trend does not favor conservative machine design, reliability is now even more important than in the past. All these requirements can only be met when the thermal performance of the machine is incorporated in the design.

1.1.1 Thermal modelling

The importance of thermal modelling of electric machines is seen in literature. Top technical journals like the *IEEE Transactions on Industrial Electronics* has, for example, published a *Special Section on Thermal Issues in Electric Machines and Drives* in October 2008 [1]. At the well respected

International Conference on Electrical Machines (ICEM 2010), various authors presented thermal work on electric machines [2], some of which were again published in a special section in the above mentioned journal.

Losses result whenever energy conversion occurs, as is the case in electric machines. Losses are responsible for the temperature rise inside an electric machine. The temperature rise in turn influences the material properties, like resistivity and magnetic residual flux density. A change in machine operation will thus result from a change in temperature. Thermal models should therefore also be used when controlling an electric machine.

Thermal modelling and design can be done in various ways. Sizing factors, e.g. maximum current density, can be imposed during the electromagnetic design of the machine. These are usually based on past experience. Another way is compiling a thermal model once the electromagnetic design has been completed to check whether temperatures are within acceptable limits. This can be used to determine cooling system requirements, or force a redesign of the machine. A coupled model which includes the electromagnetic and thermal domains, as well as the interaction between them, can also be used. This is the preferred choice when high energy density is required.

The objective of a thermal model is to predict the temperature distribution and heat flow in a material. The heat flux in a solid is described by the law of heat conduction (or Fourier's law) as shown in (1.1). This is used to derive the diffusion equation for Cartesian coordinates as shown in (1.2) [3], which is a partial differential equation (PDE) of three spacial dimensions (x, y, z) as well as time (t). The temperature distribution can be determined by solving the diffusion equation, either by analytical or numerical techniques. Numerical methods like finite element, finite difference, finite volume and the boundary element method are widely used to solve the diffusion equation in two (2-D) and three (3-D) dimensions. Lumped parameter (LP) thermal models are based on the one dimensional (1-D) solution of the diffusion equation. Most modern work use LP for cylindrical components as developed by P.H. Mellor *et al.* during thermal modelling of electric machines [4]. The diffusion equation can be solved using the separation of variables technique for certain problems [5].

$$\mathbf{q}'' = k \nabla T = -k \left(i \frac{\partial T}{\partial x} + j \frac{\partial T}{\partial y} + k \frac{\partial T}{\partial z} \right) \quad (1.1)$$

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t} \quad (1.2)$$

1.1.2 Thermal modelling solution methods

There is an ongoing debate between the supporters of analytical and numeric solution techniques. Numerical methods are well suited for complex geometries but they are normally very computationally expensive. The influence of a parameter can easily be seen when using analytical methods but the derivation of the equations are difficult and time-consuming. Anisotropic materials can easily be included in a numerical solution and analytical methods are the preferred choice for optimization. Personal preference and experience also play a big role. LP

thermal models closely resemble electric circuit models, something very familiar to electrical engineers. On the other hand, Fourier series and Bessel functions, found in exact analytical solutions of the diffusion equation may be more well known to mathematicians than engineers. Whatever method used, making good assumptions and realising the limitations of the method and assumptions are crucial. Thermal phenomena are three dimensional and time dependent. Assumptions can usually be made to reduce the model to 1-D or 2-D, without significantly compromising the accuracy of the results.

Exact analytical solutions in 2-D have been used for electromagnetic modelling of various types of electric machines. Thermal modelling on the other hand is mostly done using numerical or LP methods. Very few, if any, recent work has been published where exact analytical solutions of the diffusion equation were used for thermal modelling of an electric machine. Some of the reasons for this were given in the previous paragraph.

The effect of temperature on the permanent magnets (PMs) and winding can cause local faults even if the average temperature is at a safe level. This is why thermal models are often used to determine the "hotspot" temperature - the warmest part in a component. If the hottest point in the component is within acceptable limits, then the whole component will be. The winding is a distributed heat source since each current carrying conductor causes Joule losses. Special care must be taken when working with distributed heat sources, especially when using LP methods. Applying the heat generated through the winding at a single point result in an incorrect temperature [3].

1.1.3 Permanent magnet synchronous machines

Work is constantly being done on new machine types. Some of the requirements are high speed, high torque, manufacturability and fault-tolerance. Most applications require brushless operation, making the establishment of rotor flux with permanent magnets (PMs) common. Permanent magnet brushless direct current machines and permanent magnet synchronous machines (PMSMs) are becoming more popular, both using PMs to establish the rotor field. The former are driven using trapezoidal voltage waveforms and PMSMs using sinusoidal voltage waveforms. The PMs are usually made from rare earth materials (Nd-Fe-B or Sm-Co) which has special thermal requirements.

PMSMs offer various advantages in terms of power density, electrical efficiency, power factor, brushless operation and dynamic capability (torque-to-inertia ratio) [6–9]. High power density enables a PMSM to be physically smaller than another type of machine. In high speed applications a small rotor diameter results in smaller centrifugal forces acting on the magnets, thus simplifying rotor design and reducing magnet cost. The high electrical efficiency is a result of lower rotor loss since rotor currents are not needed to establish the rotor magnetic field. The heat generated in a PMSM rotor caused by eddy-currents can be reduced by using segmented magnets at low speed, or a shielding cylinder at high speeds [10]. The shielding cylinder can also help to retain the magnets at high speed.

In a PMSM, the most sensitive thermal components are the PMs and the stator winding. Overheating of the winding leads to insulation breakdown which causes short circuits in the wind-

ing. Magnetic flux reduction and eventually demagnetization are the results of heating PMs, as can be seen in Figure 1.1. Increasing the temperature decreases the residual flux density and coercivity. The knee of the BH curve can more easily be reached, causing a change in the PM magnetic characteristics when cooling down. Since PMs and the stator winding are crucial in machine operation, accurate thermal models are needed to predict the temperatures in these sensitive machine sections.

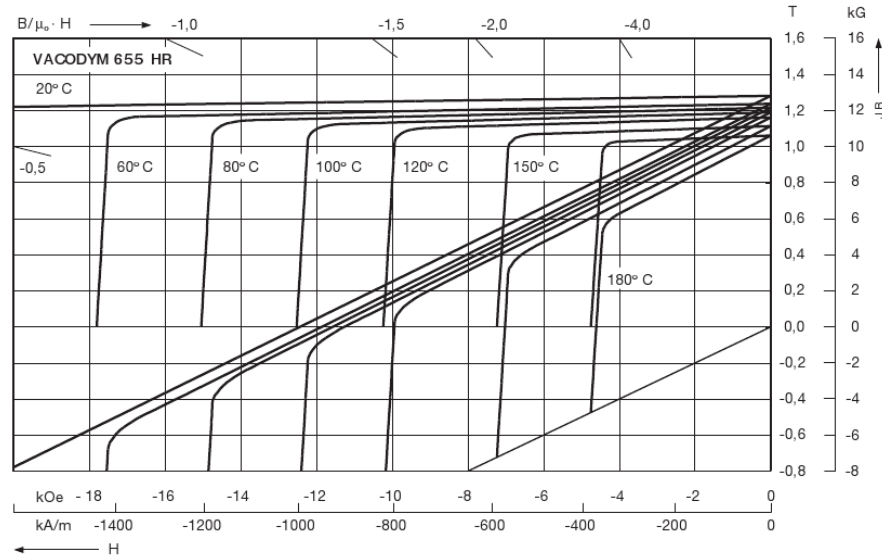


Figure 1.1: Temperature dependence of VACODYM 655[11]

Applications of PMSMs range from domestic to healthcare to aerospace. These machines are very well suited as on-board generators on boats, aircraft, buses and electrical vehicles [6]. Direct drive wind generators using PM excitation of 1.5 MW and larger have been constructed [12]. High speed applications include: high speed energy storage [13], high speed automotive applications [14] and aircraft fuel pump drives [15], to name but a few.

This section discussed the international trends in thermal modelling of high speed electric machines. Coupled modelling which simultaneously solves multiple domains, like the thermal and electromagnetic domain, is worthwhile to explore. The use of exact analytical solutions in electric machines have not been done extensively as far as thermal behaviour is concerned. In a PMSM, the PM and winding temperature distributions have a large effect on the performance and lifetime of the machine.

1.2 Test platform

The McTronX research group of the North-West University researches and develops mechatronic systems, including active magnetic bearings and PMSMs. These technologies can be combined in applications like high speed flywheel energy storage systems and gas blowers. The group has also developed a high speed PMSM testing platform called the TWINS. This

system consists of two 4 kW machines with directly connected axes. Roller element bearings are used in the TWINS. Neodymium-Iron-Boron (Nd-Fe-B) magnets, sintered into a cylindrical form and magnetized in the radial direction, supplies the rotor's magnetic field. The PM is surrounded by an INCONEL[®] shielding cylinder to ensure the rotor can withstand the centrifugal forces at 30000 r/min, the maximum rotational frequency. The machines can be operated in motoring or generating mode, thus one machine can variably load the other. This platform is suited for thermal analysis since it is equipped with temperature sensors.

The machines are internal rotor, radial flux machines. They are three-phase machines with one pole pair per phase and a single slot per pole per phase. A radial cross section is shown in Figure 1.2 and an axial cross section is shown in Figure 1.3. The slotless design and solid cylindrical PM can clearly be seen in the radial cross section. In order to investigate the thermal behaviour of the machine, resistive thermal devices (RTDs) were placed at critical points in the machine. An infrared temperature sensor is used to measure the PM temperature. The location of the temperature sensors are shown in Figure 1.3.

The rotor shaft is made from AISI 304 stainless steel. The rotor and stator laminations are made from M270-35A, 0.35 mm thick silicon steel. The PM is a forged cylinder which is magnetized in a single radial direction, manufactured from VACODYM[®] 655 (Neodymium-Iron-Boron). The magnetic flux around the magnet circumference will be a sine function of the angle at a constant radius. This results in a sinusoidal back emf. The rotor laminations were shrink fitted onto the shaft and the PM glued to the rotor laminations. The shielding cylinder were shrink fitted onto the PM. The stator winding was threaded through a tufnol coil former, which slides into the stator laminations. The stator laminations slide into the stator housing, which is manufactured from ST 52 hollow bar. High speed deep groove, ceramic ball bearings were used to ensure the maximum design speed can be reached [16]. The mechanical air gap is 0.5 mm. The TWINS' dimensions are listed in Appendix A, Table A.1.

The electromagnetic design of the TWINS was done by the McTronX group using analytical methods similar to those found in [13]. No thermal testing or modelling have been done on

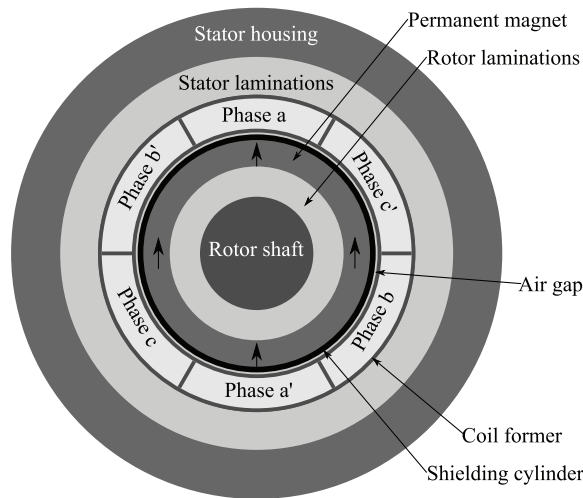


Figure 1.2: Radial cross section of TWINS

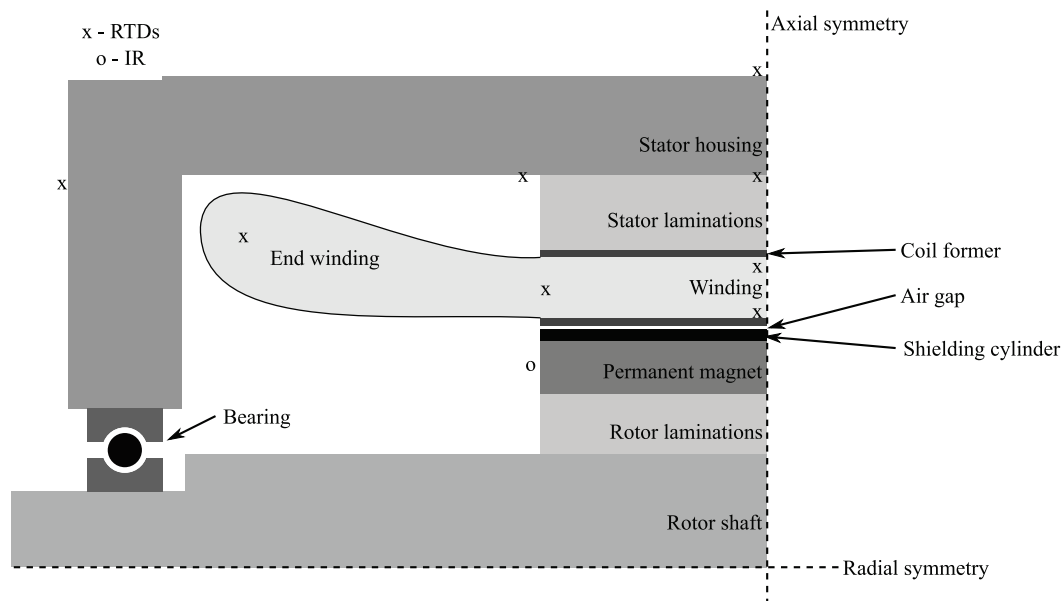


Figure 1.3: Axial cross section of TWINS

these machines. The temperature probes installed in both systems were only used for monitoring critical operating criteria like maximum PM and winding temperature. Figure 1.4 shows a block diagram of the TWINS. Both machines are connected to a three-phase voltage source inverter operating from a 310 VDC bus. Through an isolating transformer, the 380 VAC supply is transformed to 210 VAC, which is full-wave rectified to supply the 310 VDC. The temperature sensors' outputs are digitized by a dSPACE® controller. Through a connection to a personal computer (PC), the temperature values are then displayed and recorded using ControlDesk®.

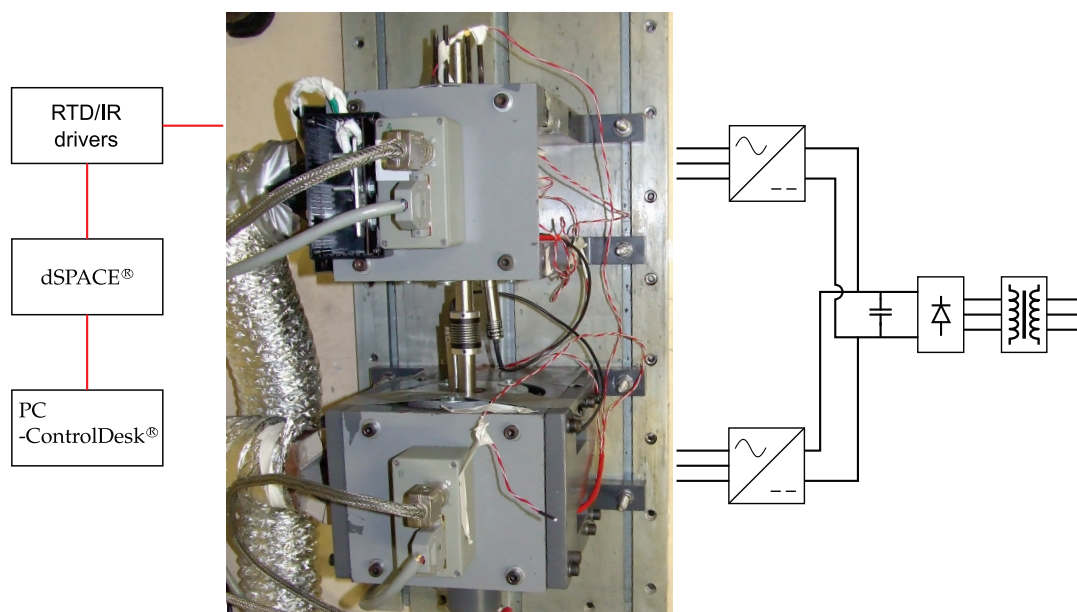


Figure 1.4: Block diagram of the TWINS

Forced cooling is used in the TWINS, as shown in Figure 1.5. There are holes in the stator housing on either side of the machine, at both of the end windings. Air is forced through this area between the stator housing and end windings, removing heat by forced convection.

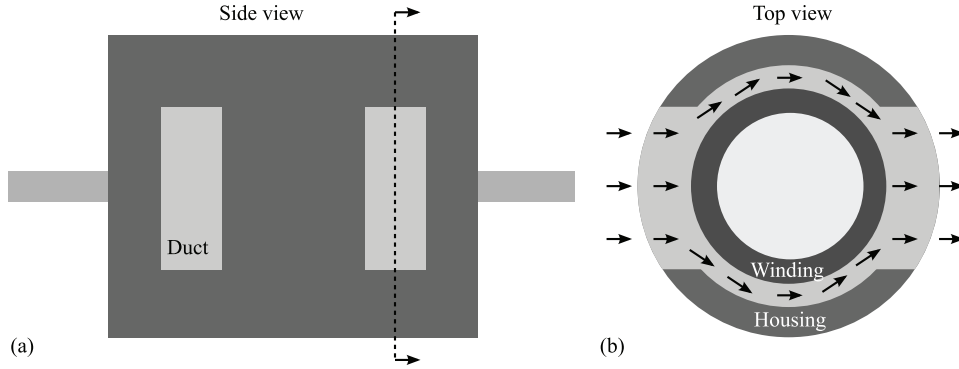


Figure 1.5: Forced cooling of TWINS: (a) side view; and (b) section view.

1.2.1 Thermal issues of the test platform

This section discusses some of the thermal problems found in the TWINS. By addressing these problems for a specific machine (TWINS), some general conclusions can be drawn.

Thermally fragile parts

The thermally most sensitive parts of a PMSM are the PMs and stator winding. Overheating causes PM demagnetization, thus removing the rotor magnetic field and rendering the machine useless. To accurately model the temperature distribution of the PM is thus very important. Stator winding insulation can also fail due to overheating. This can cause inner winding short circuits which will seriously hamper the machine operation. In extreme cases, the whole winding can be destroyed. The machine drive can also be damaged if adequate protection against winding short circuits is not in place.

Shielding cylinder

INCONEL[®] was used to manufacture the containment (shielding) cylinder due to its good mechanical properties. It is not a very good electromagnetic shielding material due to its high electrical resistivity. The purpose of an electromagnetic shielding cylinder is keeping high frequency eddy-currents from flowing in the permanent magnet. The induced eddy-currents are a function of the magnetic field strength and independent of the material. The eddy current loss can be reduced by reducing the resistance. The skin depth (δ) is given by

$$\delta = \sqrt{\frac{2}{\omega \sigma \mu}} \quad (1.3)$$

where ω is the angular frequency, σ is the conductivity and μ is the permeability. A good shielding cylinder material is copper, due to its high electrical conductivity. The permeabilities of INCONEL[®], Nb-Fe-B and copper are < 1.05 , thus the skin depth is only influenced by the conductivity of these materials [11]. The resistance ratio between copper and Nb-Fe-B is:

$$\begin{aligned} \frac{R_{PM}}{R_{Cu}} &= \frac{\sigma_{Cu} \delta_{Cu}}{\sigma_{PM} \delta_{PM}} \\ &= \sqrt{\frac{\sigma_{Cu}}{\sigma_{PM}}} \\ &= 9.96 \end{aligned} \tag{1.4}$$

This means that using a copper shielding cylinder can potentially decrease the eddy-current loss on the rotor by an order. INCONEL[®] and Nb-Fe-B have similar conductivity, thus the INCONEL shielding cylinder will not decrease the rotor eddy-current loss. It is expected that the rotor will be heated significantly by the high frequency current caused by the voltage source inverter (VSI) drive. Empirical investigation into the effect of the shielding cylinder is therefore necessary.

Cooling

Forced convection cooling is most commonly used to cool the outside frame of an electric machine through rotor connected fans. Direct cooling of the end winding should result in better heat removal since it is closer to the major heat source. The forced convection must be included into the TWINS' thermal model and should also be investigated empirically.

In the preceding sections some of the thermal issues regarding high speed PMSMs, and specifically the TWINS test platform, were discussed. The research problem can now be formulated.

1.3 Research problem

The focus of this thesis is the development and verification of an analytical thermal model for a high speed PMSM. The stator winding and permanent magnets are of great thermal importance and should receive the most attention. Verification is done using the TWINS system, thus investigating all real-world effects.

1.4 Issues to be addressed and methodology

In order to address the research problem, the following issues must be addressed. The methodology used to solve these issues is also discussed.

Background: It should be shown from the literature that the proposed contributions are indeed original. The main thermal modelling phenomena and methods must be explored. The

losses in electric machines, especially those found in high speed PMSMs should also be investigated.

Derive analytical models for the PM and the stator winding: Using the separation of variables method, the diffusion equation can be rewritten as two ordinary differential equations (ODEs). The general solution should be derived and then the boundary condition constants need to be solved from the appropriate boundary conditions.

Verification of analytical models using FEM: FEM will be used to verify the 2-D distributed analytical model. This will ensure that the derived model is correct and no derivation errors were made. The accuracy of the assumptions can only be verified by comparing the model to experimental results.

Develop a LP model for the rest of the machine: The method developed by Mellor *et al.* is applied to the entire high speed PMSM. This model can be used to determine the temperatures in key locations as well as the heat flow throughout the machine.

Combining the analytical models: The LP model does not include axial heat flow in the rotor and predicts the average temperature of a part. The distributed model can be used to address these shortcomings. The heat flowing into the rotor from the PM can be determined using the LP model and is one of the inputs for the distributed model. The heat flow in the axial directions as well as the temperature distribution of the PM can be determined using the distributed model. A hybrid model is thus used to model the PMSM.

Calculation of the machine losses: Machine losses serve as inputs to the thermal model and must be determined. A 2-D analytical model is used to determine the stator losses. The rotor eddy current loss is the prominent loss on the rotor and is calculated using a simple LP model.

Experimental variable determination: Convection and interface resistances are usually determined empirically and this is also done in this thesis. A series of experiments are done to determine these resistances and the results compared with theoretical calculations. Assumptions on bearing loss and cooling techniques can also be evaluated at this stage.

Experimental validation: After all the parameters are known, the model can be verified through an experiment.

Model prediction: The thermal model can now be used to predict the machine temperatures in conditions different from the experimental conditions.

1.5 Contributions

The contributions of this study are obtained by applying existing methods to a new field or in a new way. The following contributions are envisioned:

Distributed thermal model: The derivation of a 2-D distributed thermal model for the PMs on the rotor, with convection heat transfer on three boundaries and a surface heat source on the fourth is a contribution.

Hybrid thermal model: Combining the distributed and LP models to achieve a detailed temperature distribution of the PM has not been encountered in literature.

Experimental investigation: Experimental investigation of the influence of an INCONEL[®] shielding cylinder on the thermal model will advance this important aspect of high speed machines. Through a series of tests the main loss contributors can be identified and quantified.

1.6 Thesis overview

The thesis has the following structure:

Chapter 2 - Background The contributions claimed must be supported by literature. The main heat transfer mechanisms found in electric machines are discussed in detail as well as the techniques used to determine the temperature distribution in a machine. Losses are an integral part of thermal modelling and are discussed. An overview of the current research is given and the case made for the originality of the contributions.

Chapter 3 - Lumped parameter thermal modelling The LP method as proposed by Mellor [4] is discussed in detail in chapter 3. The method is applied to the TWINS machine and the interaction of the LP and exact model is given.

Chapter 4 - Distributed thermal modelling The exact solution of the temperature distribution of the PM in 2-D is derived in this chapter. A 1-D model for the stator winding is derived and both of these are validated using a numerical software package.

Chapter 5 - Loss modelling The loss mechanisms found in a high speed slotless PMSM are discussed. A 2-D analytical magnetic model is derived and used to calculate the stator losses. A simple LP model is used to model the rotor eddy current loss.

Chapter 6 - Experimental model derivation Some thermal parameters are usually determined empirically. A series of tests are performed to determine the convection and interface resistances. A better understanding of the thermal behaviour of a high speed PMSM is also gained.

Chapter 7 - Model evaluation The thermal model is used to predict the machine's temperature in conditions different from those used during the experiments in the previous chapter. Using a sensitivity analysis, the influence of some parameters on the machine temperatures is explored. Suggestions are made to reduce eddy current rotor loss and interface resistances.

Chapter 8 - Conclusions and recommendations In the final chapter the findings of this thesis are combined and the contributions revisited to evaluate their worth. Recommendations for future work are also made.