THERMAL ANALYSIS
- LUMPED-CIRCUIT MODEL AND FINITE ELEMENT ANALYSIS

Y.K. Chin, E. Nordlund
Royal Institute of Technology (KTH)
Sweden

D.A. Staton
Motor Design Ltd.
United Kingdom

Abstract

This paper presents the thermal analysis of Permanent Magnet Synchronous Motors (PMSMs) for electric vehicle traction applications. Modern thermal design techniques can be classified into two general methods, analytical lumped circuit and numerical analysis. It is the aim of this paper to investigate the strengths and weaknesses of the two approaches. Two commercially available thermal design packages, Motor-CAD and FEMLAB, are used in our investigation. Motor-CAD is a 3-dimensional (3D) lumped circuit analysis package dedicated to the thermal design of motors. FEMLAB is a multi-physics 2- and 3-dimensional finite element analysis (FEA) package.

Keywords
Thermal, Permanent Magnet Synchronous Motors, Lumped-circuit, Finite Element Method (FEM).

1 INTRODUCTION

Studies focusing on the thermal aspects of a design are often overlooked or outweighed by the electromagnetic design analysis. This is despite the fact that thermal constraints must be kept within certain limitations when achieving the torque and power requirement of the design. Traditionally the thermal performance of a new motor design has been predicted based on a few simple parameters such as housing heat transfer coefficient, winding current density or motor thermal resistance. The figures used for such parameters might have been estimated empirically from experimental tests on existing motors, or from simple rules of thumbs [1,2]. The problem with such a design approach is that no insight is gained of where the thermal design may be compromised and therefore where design effort should be concentrated [3]. The approach can also be very inaccurate leading to incorrectly sized motors.

Modern thermal design techniques suitable for use in the design process can be divided into lumped circuit and numerical analysis techniques. Two such commercially available thermal design packages, Motor-CAD [4] and FEMLAB [5], are used in our investigation. Motor-CAD is a dedicated motor thermal design package based on analytical thermal lumped-circuit analysis. FEMLAB is a multi-physics finite element analysis package. It solves a system of partial differential equations (PDEs) for a numerical mesh covering the motor cross-section/volume.

2 GEOMETRY STUDIED & LOSSES

Figures 1 to 3 show the geometry of the 9.4 kW PMSM design example investigated in this study. The design is an inset permanent magnet (IPM) motor topology, with radially magnetised neodymium iron boron (NdFeB) magnets. It has a stator outer diameter of 188 mm and an active length of 165 mm. The motor is designed for a wide operating speed range (0 to 3900 rpm with rated speed of 1500 rpm). Figure 1 shows a 3-dimensional view of the studied geometry. Figures 2 & 3 show the geometric input required by Motor-CAD.

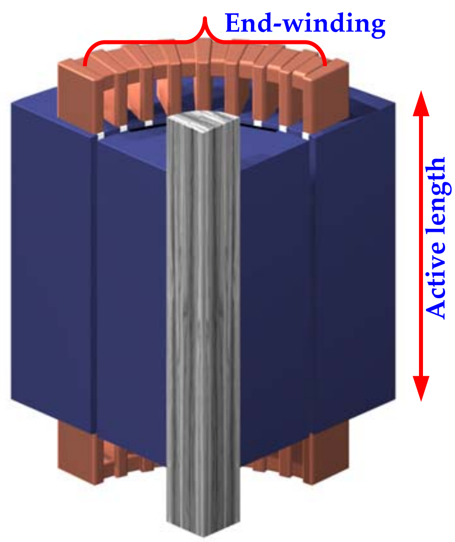

Figure 1: PMSM geometry studied.

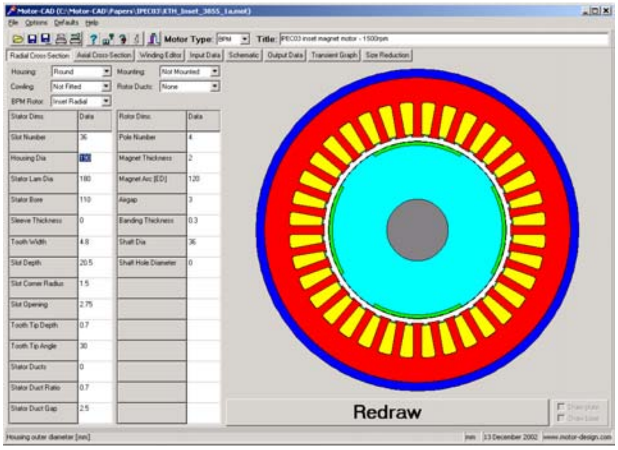

Figure 2: Motor-CAD radial cross section editor.

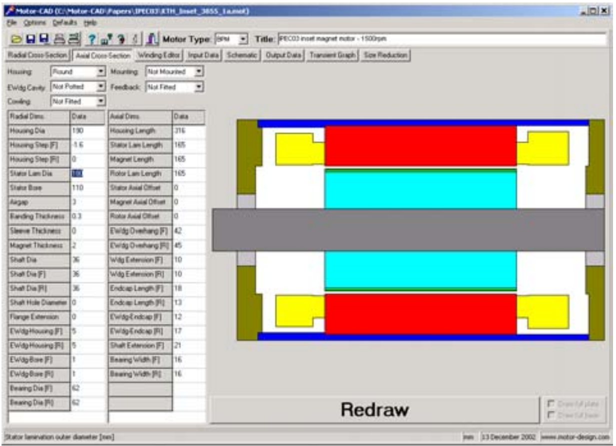

Figure 3: Motor-CAD axial cross-section editor.

Different operating losses generated in various regions are calculated accordingly and form heat sources in the thermal analysis. Copper losses are a function of temperature as the winding resistance is temperature dependent. This can easily be taken into account in the lumped circuit approach as the speed of calculation is so fast that the added iteration required to make the losses (input to the model) a function of temperature (output from the model) is negligible. In the FEA package this is more difficult to apply due to the added complexity to program the iterative solution and the resulting longer execution times.

Iron losses in stator yoke, teeth and rotor back can be estimated analytically [6,7] or numerically with FEM calculations. Figure 4 illustrates the predicted iron losses in various parts of the stator from the rated speed to the maximum operating speed. In this investigation, thermal analysis is applied when the motor is running at rated speed and 2.57 times the rated speed, as point A and B in figure 4.

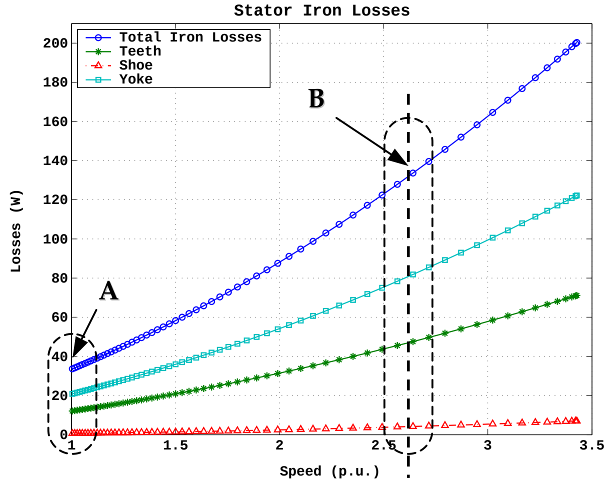

Figure 4: Analytically predicted stator iron losses. A- rated speed; B-2.57 times the rated speed.

3 LUMPED-CIRCUIT ANALYSIS

The Motor-CAD thermal model is based upon lumped-circuit analysis. It represents the thermal problems by using the thermal networks, analogous to electrical circuits. The thermal circuit in the steady state consists of thermal resistances and heat sources connected between motor component nodes. For transient analysis, the heat/thermal capacitances are used additionally to take into account the change in internal energy of the body with time. Thermal resistances for conduction and convection can be obtained by:

$$R_{conduction} = \frac{l}{A \cdot k} \qquad [\text{K/W}] \qquad (1)$$

$$R_{convection} = \frac{1}{A_{cool} \cdot h} \qquad [\text{K/W}] \qquad (2)$$

where l is the distance between the point masses and A is the interface area, k is the heat conductivity, A_{cool} is the cooling cross section between the two regions and h is the convection coefficient – calculated from proven empirical dimensionless analysis algorithms [9]. The heat capacitance is defined as:

$$C = V \cdot \rho \cdot c \qquad [\text{Ws/K}] \qquad (3)$$

where V is the volume, ρ is the density and c is the heat capacity of the material. Figure 5 presents the schematic diagram of a steady state thermal network of a PMSM developed by Motor-CAD. As described earlier, the thermal resistance values are automatically calculated from motor dimensions and material data. The accuracy of the calculation is dependent on knowledge of the various thermal contact resistances between components within the motor, e.g. slot-liner to lamination and lamination to housing interface.

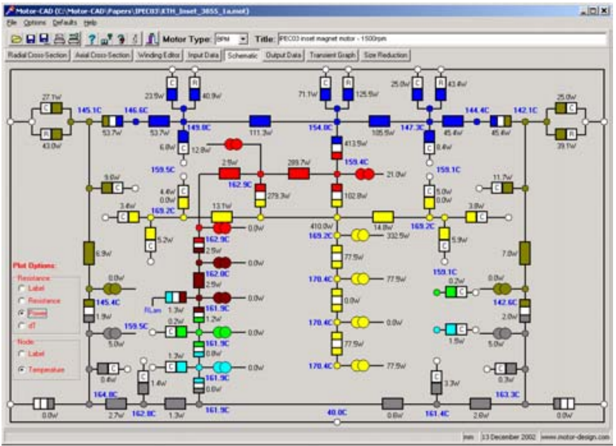

Figure 5: Motor-CAD steady-state schematic.

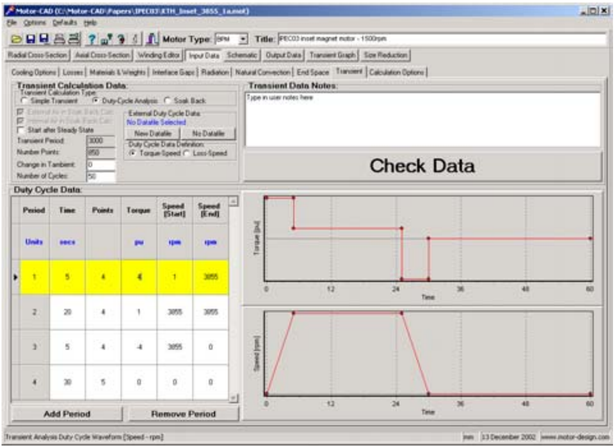

Figure 6: Motor-CAD duty-cycle editor.

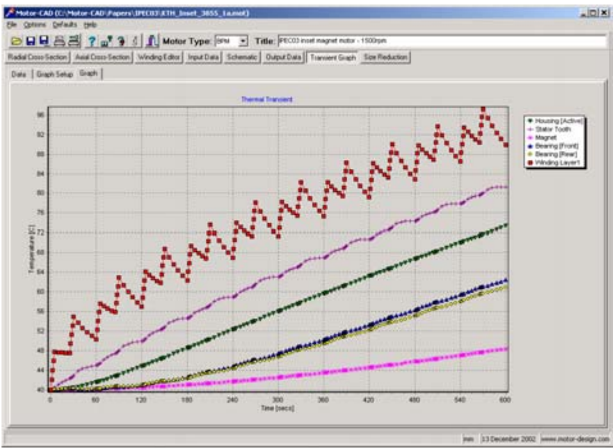

Figure 7: Motor-CAD transient waveform.

The lumped-circuit approach is ideal for carrying out sensitivity analysis on manufacturing phenomena such as interface gaps between components or regions. These can have a substantial influence in the analysis, particularly in highly rated machines. The near instantaneous calculation capabilities of Motor-CAD evince the possibilities to run "what-if" scenarios in real time.

It is essential to consider both the electromagnetic and the thermal design aspects when obtaining a true optimum design. There is a strong interaction between two disciplines, i.e. the losses are critically dependent on the temperature and vice versa. It is impractical to study one without considering the other. In this regard, it is much easier to link a lumped circuit package to an analytical electromagnetic motor design package than a numerical analysis package. In fact this capability is now available between Motor-CAD and SPEED[1] software [10] using ActiveX links.

Figure 6 shows the duty-cycle editor provided in Motor-CAD. This can be used to define load cycles, in terms of torque and speed against time. The waveform shown is for a repetitive duty cycle of 60 Nm acceleration from 0 to 3855 rpm in 5 seconds, then a continuous load of 15 Nm for 20 seconds followed by a 5 second 60 Nm deceleration period. There is then a 30 second rest period. Figure 7 shows the resulting thermal transient for the different components within the machine for 10 cycles for the load cycle. It is seen that the winding has a much smaller thermal time constant than the bulk of the machine and so heats and cools at a much faster rate than the other components – this in one reason why accurate thermal transient analysis is essential, especially when large overload periods are encountered.

4 FINITE ELEMENT ANALYSIS

FEMLAB [8] is employed in this study for the numerical analysis. The basic mathematical structure with which FEMLAB operates is a system of partial differential equations (PDEs). FEMLAB applies the finite element method (FEM) when solving the coupled non-linear PDEs that describe the thermal network. For the PDE formulation, heat transfer is governed by the heat equation as:

[1] SPEED is an analytical electromagnetic software for electric motor design developed by the SPEED Laboratory at Glasgow University, UK.

$$\rho \cdot c \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q \qquad (4)$$

where Q is the external heat source and it is given by a single quantity Q in 3-D analysis. For 1-D and 2-D, it can be represented with the additional transversal heat sources as:

$$Q + h \cdot (T_{ext} - T) + C_{rad} \cdot (T_{amb}^4 - T^4) \qquad (5)$$

where C_{rad} is the emissivity constant of the surface and T_{amb} is the ambient temperature. The boundary conditions applied in the analysis are the symmetry, fixed temperature condition and heat flux sources. Symmetry boundary condition implies a zero inward boundary heat flux, equivalent to an insulated boundary condition. A fixed temperature condition is used to specify a desired temperature on the boundary. They can be denoted by the following equations:

$$n \cdot (k \nabla T) = 0 \qquad (6)$$

$$T = T_0 \qquad (7)$$

The boundary conditions can also be of Neumann type where the inward heat flux is given by:

$$n \cdot (k \nabla T) = q + h \cdot (T_{ext} - T) + C_{rad} \cdot (T_{amb}^4 - T^4) \qquad (8)$$

where $h(T_{inf}-T)$ is known as Newton's law of cooling or convective heat transfer to the surroundings. Various heat sources (losses) are placed in the respective sub-domains of the simulated geometry. Heat sources considered are the iron losses and the copper losses equally distributed over the specified region. For instance, the winding loss per slot is allocated by distributing the total copper loss into the total number of slots equally, i.e. 410 Watts/36 slots = 11.4 Watts per slot. The temperature distribution has been simulated at the rated condition and at a speed of 2.57 times the base speed, as depicted in figure 8 and figure 9 respectively. For the 3-D analysis, the geometry is obtained by extruding the existing 2-D geometry in the z-direction. Only one eighth of the machine is required for the simulation due to the axis-symmetry of the geometry studied.

An "air box" is added around the end-winding region to model the convection heat transfer effectively between the surfaces of the active motor parts and air. End-windings are modelled by extending the wire bundles from the active region and additional copper material are placed between the extruding bundles. The inject loss into the active and end-winding sections of the winding are divided according to the volume ratio. A convective heat transfer coefficient is applied to the surface of the end-windings with the external temperature equals to the air box temperature. A precise figure for this coefficient is very difficult to be determined as it varies with respect to the temperature and properties of the air flow [9]. A formulation similar to that used in Motor-CAD can be used:

$$h = k_1 \cdot (1 + k_2 v)^{k3} \qquad (9)$$

for which many authors have published empirical data. Figure 10 shows the variation of h with respect to the velocity ν for values of k1, k2 and k3 as proposed by [11-15].

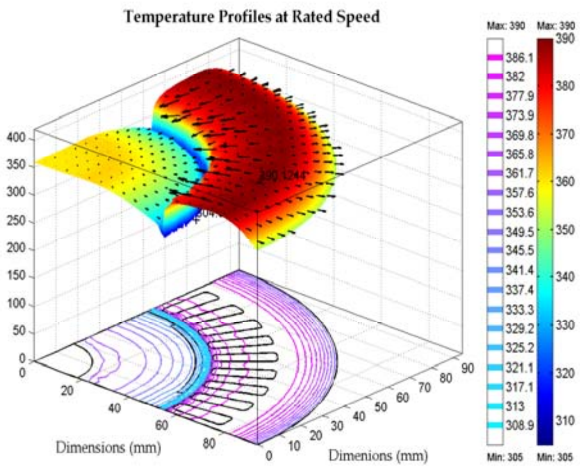

Figure 8: Temperature profiles at rated speed: 1500 rpm.

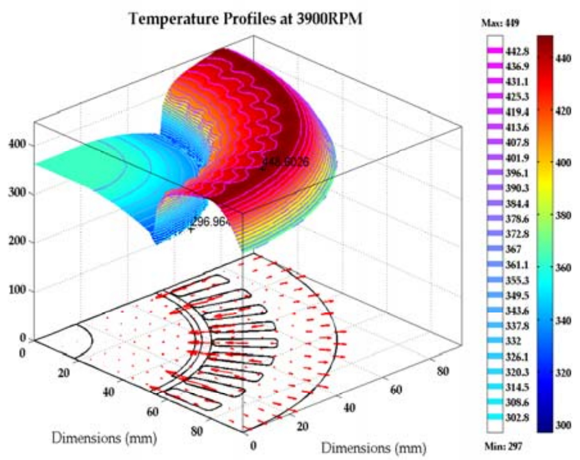

Figure 9: Temperature profiles at 3900 rpm.

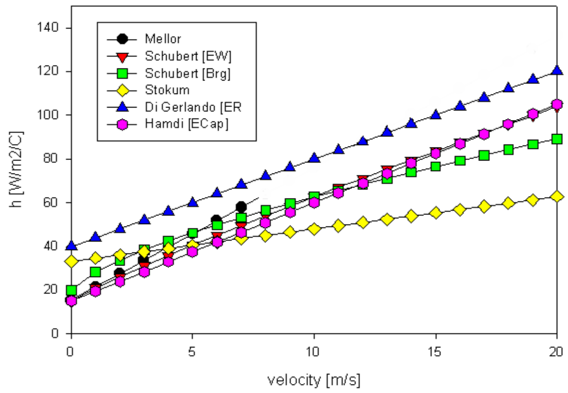

Figure 10: End-winding heat transfer coefficient.

5 RESULTS AND DISCUSSIONS

The motor temperature distributions at two operating speeds are estimated by Motor-CAD and FEMLAB and show a good agreement. The thermal "hot regions" are in the stator slots and teeth where the copper and iron losses are generated, as illustrated in figures 5 & 8. When the motor is running at a high speed in the field-weakening region, a considerable rise in temperature is calculated due to the significant increase in losses, as shown in figure 9.

The influences of various thermal properties on the temperature distribution have been investigated. The stator temperature profile variation with air gap temperature and lamination thermal conductivity are presented in figures 11 and 12 respectively. Similar studies have been carried out using Motor-CAD with similar trends for the nodal temperatures being seen (not show here due to space limitations). The FEMLAB results do show more detail of the variation in temperature thought thermally conductive regions – but at the expense of longer execution times.

The thermal conductivity of the silicon iron lamination decreases as the silicon content increases [16]. A better heat transfer through the stator back is evident with a low percentage silicon iron. However, there are more eddy current losses. This balance should be considered at the design stage. An overheated magnet can be detrimental to the machine performance. Figure 13 demonstrates the use of rotor cooling ducts to keep the magnet temperature within the design constraints. The axial temperature profiles in various geometric regions are show in Figure 14 and the end-winding temperature distribution presented in figure 15.

The temperature in the end-winding is highly dependent on the values of convection and radiation coefficients. In this study, the radiation coefficient is neglected and the convective coefficient applied is according to figure 10.

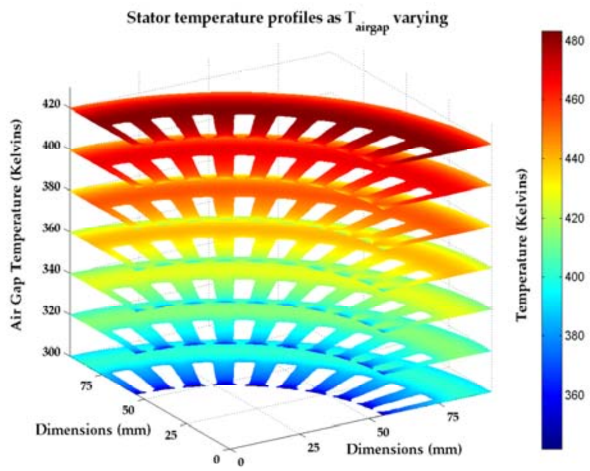

Figure 11: Stator temperature distributions for various air gap temperatures.

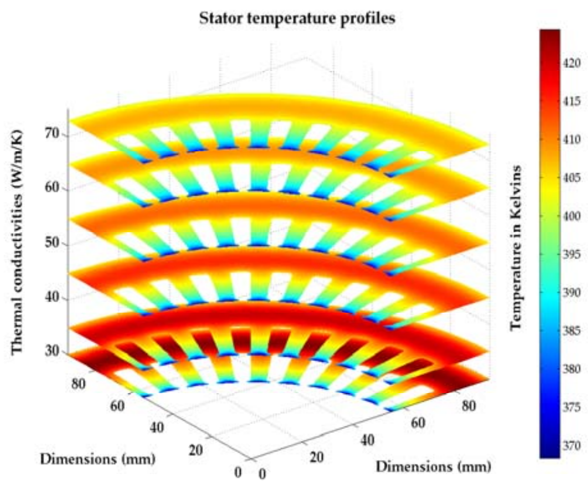

Figure 12: Stator temperature with various lamination thermal conductivities.

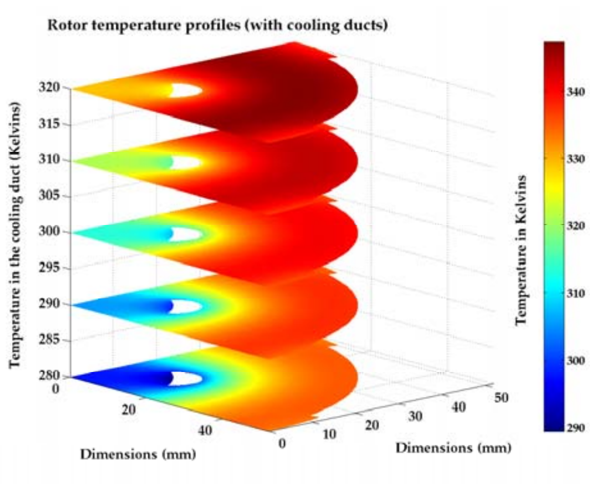

Figure 13: Effect of the cooling on rotor.

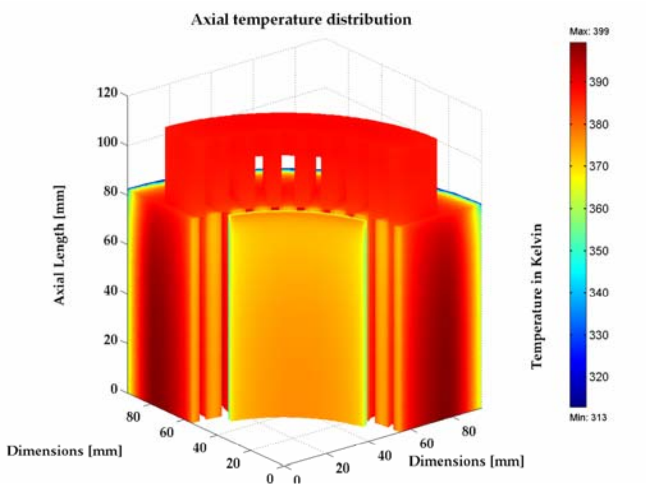

Figure 14: Temperature variation in 3-dimension.

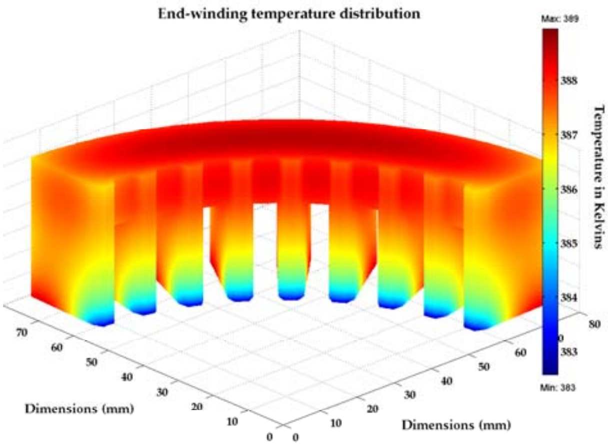

Figure 15: End-winding temperature distribution.

6 CONCLUSIONS

The thermal analysis of a PMSM has been demonstrated using two commercially available packages, Motor-CAD and FEMLAB. The strengths and weaknesses of each of the packages have been investigated. Motor-CAD is based on analytical thermal lumped circuit analysis. Its main strengths are in its ease of use and its ability to account for difficult motor related phenomena such as winding impregnation goodness and interface gaps between components. It has a clear advantage over numerical analysis in terms of calculation speed – this being very important when carrying out sensitivity analysis and for modelling thermal transient with complex duty cycle loads. It main weakness is that the user can only model the configurations available in the software – although the range of geometries and cooling methods available are extensive.

FEMLAB is based on numerical FEA analysis. Its main strengths are that the user can model any geometric shape and it gives detail in the calculation of temperatures in conducting regions. It does have weaknesses when calculating convection at open surfaces - the alternative numerical technique, computational fluid dynamics (CFD), has clear advantages here. Much the same dimensionless algorithms as used in Motor-CAD can be used to model convection at the open boundaries. FEMLAB's main weaknesses are that it is relatively difficult and slow to input a new geometry and has long execution times. Also, the modelling of complexities such as interface gaps is more difficult than in lumped circuit analysis.

REFERENCES

[1] J.R. Hendershot, T.J.E. Miller, *Design of Brushless Permanent Magnet Motors*, Magna Physics Oxford Science Publications, 1994.

[2] Hanselman, D.C., *Brushless Permanent-Magnet Motor Design*, McGraw-Hill, 1994.

[3] D.A. Staton, *Thermal Computer Aided Design – Advancing the Revolution in Compact Motors*, IEEE International Conf. IEMDC'01, pp. 853-858, June 2001.

[4] Motor-CAD v1.6(14), Motor Design Ltd.

[5] S. Littmarck, et.al., *Math, models, motion and more*, PT Design Magazine, Penton Media, Cleveland, 2000.

[6] Y.K. Chin, J. Soulard, *Modelling of Iron Losses in Permanent Magnet Synchronous Motors with Field-weakening Capability for Electric Vehicles*, EVS19, October, 2002.

[7] K. Atallah et al., *Rotor Loss in Permanent-Magnet Brushless AC Machines*, IEEE Tran. on Ind. Appl. VOL. 36, No. 6, Nov/Dec, 2000.

[8] FEMLAB v2.30, Comsol AB.

[9] J.P. Holman, *Heat Transfer*, Seventh Edition, McGraw-Hill Publication, 1992.

[10] SPEED/Motor-CAD Import/Export Functions www.motor-design.com

[11] P.H. Mellor, D. Roberts, D.R. Turner, *Lumped Parameter Thermal Model for Electrical Machines of TEFC Design*, IEE Proc-B, Vol. 138, No. 5, Sept 1991.

[12] E.S. Hamdi, *Design of Small Electrical Machines*, Wiley, 1994.

[13] Di Gerlando, A, Vistoli, I: *Improved thermal modelling of induction motors for design purposes*, ICEM 1993, Oxford

[14] G. Stokum, *Use of the results of the four-heat run method of induction motors for determining thermal resistances*, Elektrotechnika, 1969, Vol 62, No 6.

[15] E. Schubert, *Heat transfer coefficients at end winding and bearing covers of enclosed asynchronous machines*, Elektrie, April 1968, Vol 22.

[16] G. Gotter, *Heating and cooling of electrical machines*, 1954, Springer Verlag, Berlin.