Linked Electromagnetic and Thermal Modelling of a Permanent Magnet Motor

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Abstract

This paper studies the thermal modelling of a permanent magnet motor using linked commercial design packages. The electromagnetic design is carried out using *SPEED* PC-BDC, from The University of Glasgow while the thermal simulation, to verify the thermal integrity of the machine, is carried out using Motor-CAD, from Motor Design Ltd. These two design procedures are often carried out separately but this illustrates that, in the modern Windows environment, it is often possible to link packages together and bring a step-change to the sophistication of the design procedure. The results are verified experimentally.

1 Introduction

The thermal modelling of electrical machines is still a very specialized and, to some extent, an inexact process. It is however an important process since the limit of operation of the machine is often due to the thermal limits. There are several books available which address the overall design of permanent-magnet electric machines [1]-[3] although the electromagnetic and magnetic material aspects rather than the thermal aspects take priority (but they are addressed). Many designers will set the temperatures of the machine (i.e., the winding, magnet, steel, etc, temperatures) to realistic values then carry out an electromagnetic design. This design process relies on the designer having a realistic knowledge of what the losses can be allowed in the machine, i.e., the maximum copper losses (possibly by allowing a maximum winding current density of about 5 to 7 A/mm^2) and iron losses (not allowing flux density levels higher than 1.7 to 1.9 T or even higher for low loss or high flux steels). Once the electromagnetic design is complete the cooling system will be designed to cope with the losses produced.

Commercial software packages are now available for the electromagnetic design – e.g. PC-BDC [4]. They have some thermal modelling capabilities (multi-node network of up to 10 nodes) that can help with the initial sizing. For more sophisticated thermal modelling a software package dedicated to the thermal analysis of electrical machines can be used, e.g. Motor-CAD [5]. Both packages run under the Windows OS and have full ActiveX capabilities. ActiveX is a standard method for linking programs together and transferring data.

There is a dedicated link written using ActiveX technology to transfer geometric, loss and temperature data between the two programs. Macros can also be written in separate programs such as MATLAB or VBA to call both PC-BDC and Motor-CAD. This is often done for more complex calculations such as automated optimisation, sensitivity analysis and the modelling of complex dynamic loads.

2 Example Machine

The machine took the form of a 6-pole brushless permanent-magnet servo motor. The machine operated under ac control. The machine was tested using the fitted thermocouples. The specification of the machine is given below together with the experimental results.

2.1 motor specification

The cross-section of the machine is given in Fig 1. This is obtained from *SPEED* PC-BDC from The University of Glasgow. It takes the form of a 6-pole brushless servo motor with surface mounted SmCo magnets. The winding is 3-phase with 3 coils per phase giving a single layer winding with a coil pitch of 3 slots. The rated current was 6.1A and the speed fixed at 2600rpm. The frame size was 115 with an axial core length of 74mm.
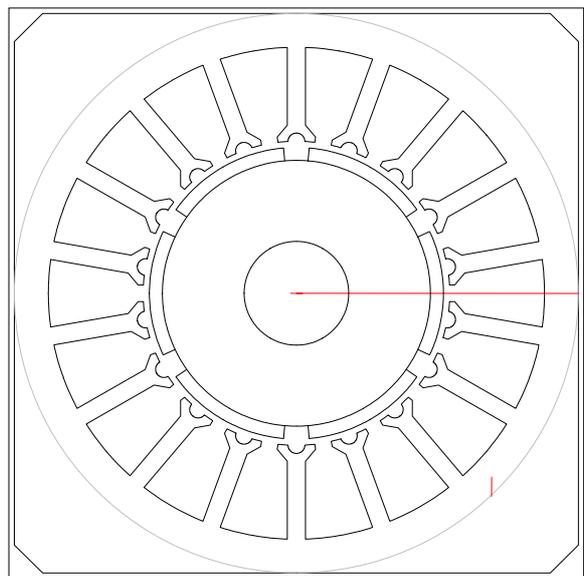
Fig. 1: Machine cross section from PC-BDC

A photograph of the machine is given in Fig. 2. The machine was flange mounted onto a simple aluminium plate.
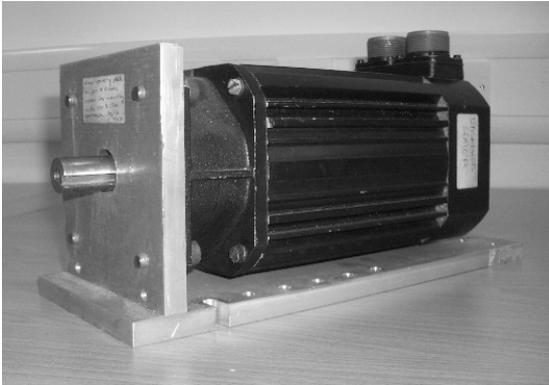
Fig. 2: Test machine

The major geometry necessary for good electromagnetic design is contained in PC-BDC and indeed there is also a 10 node thermal model that can produce reasonable temperate variation when tuned. However, for more detailed thermal modelling then Motor-CAD from Motor Design Ltd. can be used. Additional details such as fins, forced cooling, insulation impregnation goodness, foot or flange mounting, seals and interface gaps, bearings, etc can be modelled. This requires further geometry details not required by the electromagnetic design as shown in Fig. 3 (radial cross-section) and Fig. 4 (axial cross-section). It is not necessary to enter all these geometrical parameters individually since the ActiveX link passes many parameters between the two packaged automatically (as discussed later). A square section casing was chosen – the fins in Fig. 2 are very small and have little effect unless the machine is fitted with a fan. Care was taken in Fig. 4 to select the right sizing and shape for the end-caps – especially since the casing is square while the end-cap is round – also there is a gasket fitted (discussed later).
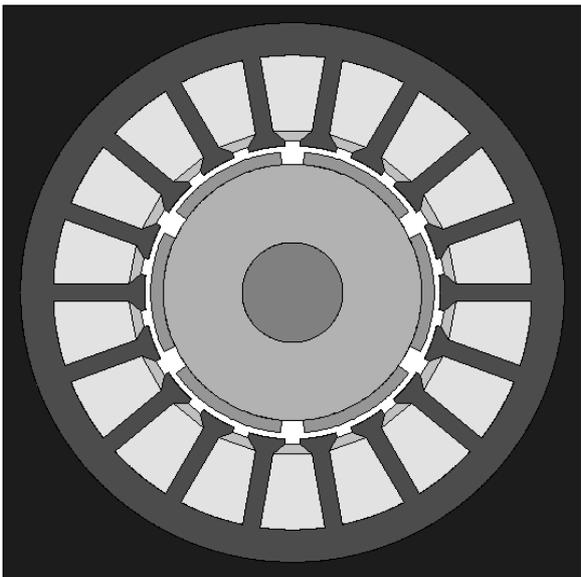
Fig. 3: Cross-section showing fining from Motor-CAD
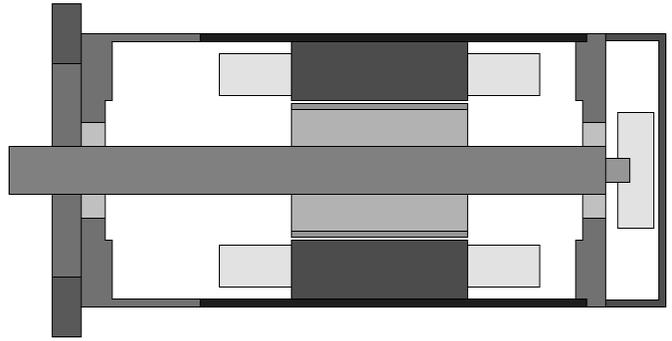
Fig. 4: Axial section

2.2 Experimental setup and thermal results

This machine could be run under either ac or dc control, however it was decide to operate under ac control. This allowed the encoder to be rotated by nearly 90º elec. so that the current was almost on the d-axis. This meant that the machine could run at rated current but with no mechanical load, i.e., the machine was artificially loaded. The flange mounting can be a source of heat sinking if bolted to large metal structure with a thermal capacity such that it acts almost as a constant temperature node; however the fixture was placed on a simple wooden bench. The machine was driven from an inverter that controlled the 3-phase sinusoidal currents with a current of 6.1 A rms.

Five thermocouples were permanently attached to the machine. The first was in the centre of the winding, one was placed in the centre of a tooth, one was embedded in the casing, one was attached to the surface of the non-drive-end winding overhang and finally the fifth was attached to the non-drive-end end housing. A sixth was also used to measure the temperature of the shaft end when stationary. These were logged using a data logger so that the temperatures could be continuously monitored during operation.

3 Experimental Results

Several results were run over time however here we will concentrate on two sets of results – the first is a simple transient run-up over three hours from the ambient, the second represents operation over a changing duty-cycle.

The first transient run-up was taken over a period of three hours as shown in Fig. 5. The peak temperature, as expected, was in the winding with a peak temperature of 144 ºC. The ambient was 24ºC. The insulation rating of the machine was Class F (155ºC with 40ºC ambient) so the test data represents a marginal result. However, it should be remembered that this machine is allowed to be flange mounted to a sizable horizontal plate during a rating test according to the NEMA standards. The plate acts as a heat sink and is supposed to represent the cooling of the device to which the motor will be coupled in practice. The plate used in the test is much smaller than allowed so that we can concentrate on analysing the cooling of the motor alone.
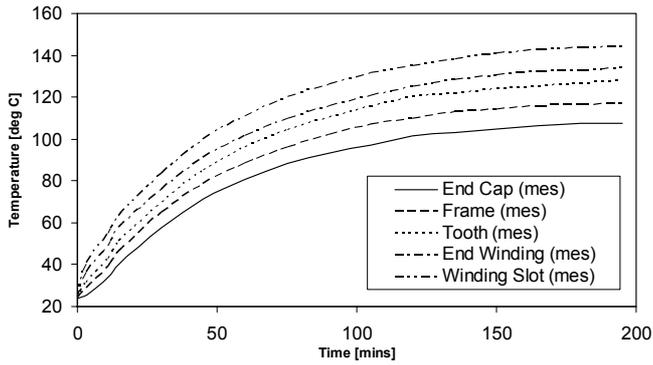
Fig. 5: Transient run-up measurements

The second test results are shown in Fig. 6. This takes the form of a thermal run-up at 2600 rpm from ambient to time T = 20 mins. The machine is then immediately brought to rest and the shaft temperature measured along with the five fixed thermocouples. After ten minutes the machine is restarted and run at 2600 for a further ten minutes. This is repeated three times followed by a further ten minute rest period, giving a total measurement period of ninety minutes. It is interesting to note that the temperature continues to rise in the shaft when stationary although they are reducing at the other locations.
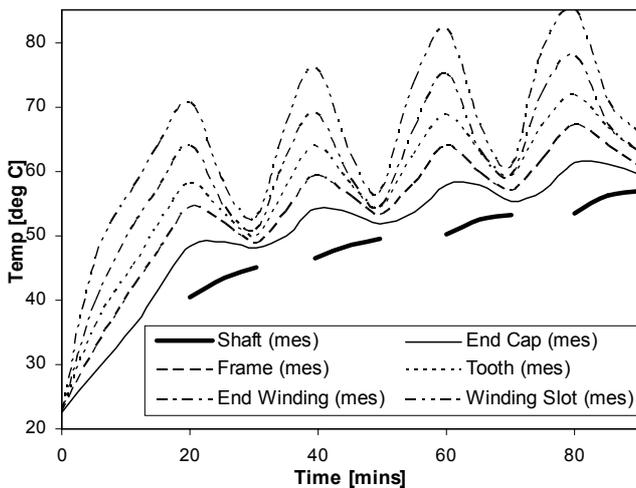
Fig. 6: Transient duty cycle measurement

4 Simulation

The machine simulations are briefly described here. The electromagnetic analysis is carried out in PC-BDC and the thermal analysis in Motor-CAD. Geometric, loss and temperature data is passed automatically between the two packages.

4.1 Linking, geometrical set-up and transient simulation

The electromagnetic simulation was initially modelled in PC-BDC. This involved the definition of the geometry, winding (turns, wire size, winding pitch, etc), materials (magnets and steel), drive (voltage, switching type, etc) and the operating point (speed, current). Performance details such as the winding resistance & inductance, current, back emf, and torque waveforms, copper and iron losses are then calculated. PC-BDC is then called from the Motor-CAD environment. The dialog that controls the data to be transferred is shown in Fig. 7. This link was developed by joint co-operation using Windows ActiveX (COM) software technology. Initially the geometry is transferred. After importing the geometry, additional geometric details relating to the flange mounting, endcaps, bearings, etc are then defined. The copper and iron losses as calculated in PC-BDC are imported into the thermal model and the temperatures predicted. These can be fed back to PC-BDC and an automated iterative process followed to make sure that the losses and temperatures tie up with each other.
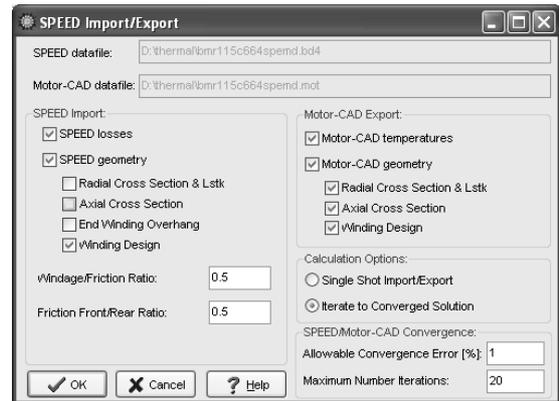
Fig. 7: *SPEED* link in Motor-CAD

The iterative linked simulation is most valuable for calculating the steady-state thermal performance. For transient thermal calculations, especially with complex duty cycle loads, Motor-CAD has a simple model that describes the variation in losses with speed, temperature and load. Data for this model is imported from PC-BDC. This includes the losses at know winding and magnet temperatures, the torque constant of the machine and the temperature coefficient of *Br* for the magnets. The copper loss is a function of load (torque proportional to current) and winding temperature (temperature coefficient of resistance for copper). Account is taken of any loss in flux due to magnet heating making it necessary for a larger current to obtain the required torque. The iron loss varies according to the variation of the magnetization and a simple relationship can be obtained from the Steinmetz equation where the iron loss is proportional to B^x, where x can be set in Motor-CAD. The default value is 1.5 although often values between 1.5 and 1.8 are suitable and this is a function of the steel material. This simple loss model does not accommodate field weakening operation at present, although a model is under development.

SPEED has a more sophisticated temperature-dependant iron loss calculation tool using a modified Steinmetz equation and it would be possible to write an ActiveX link program to do a full transient solution using the loss variation and performance calculation from *SPEED* and the thermal networking from Motor-CAD across the whole transient. The linking program just needs to control the times at which transfer of data is made between the two packages, i.e. when the loss or temperatures vary above a given threshold.

4.2 Tuning

Thermal modelling is complicated by the fact that some parameters are a function of the production procedures used, i.e., winding impregnation and interface gaps between components. Motor-CAD default values have been set to try and give reasonable results for machines made using standard manufacturing processes. The winding thermal resistance is very dependant on the impregnation – this machine had impregnation of the end-winding only so the impregnation coefficient of the active slot conductors was set to account for this. It was also found that the front end-cap was separated from the main casing by a 0.25mm thick gasket seal. This can be modelled in the thermal network by an artificially increased interface gap at that point. Experience suggests that thermal conductivity of this type of seal is about 10 times that of air so an air-gap of 0.025 mm was used to represent this. Other points that required attention were: the emissivity due to the black paint – this was set to 0.95; the materials (the casing was aluminium); experience suggests that the magnet loss should be minimal in this case. An iron loss multiplication factor of 1.8 was used in this case to account for additional loss due to the steel and manufacturing processes used.

4.3 Thermal model

The thermal network for Motor-CAD is quite sophisticated with 32 nodes. This is shown in Fig. 8; the 5 nodes below represent the nodes closest to the measured nodes and were chosen as being suitable for comparison:

- Winding Layer [4] – *winding slot*
- Housing (active) - *frame*
- Stator Tooth - *tooth*
- End Space (Rear) – *end winding*
- End Cap (Rear) – *end cap*
- Shaft (front) – *shaft at standstill*
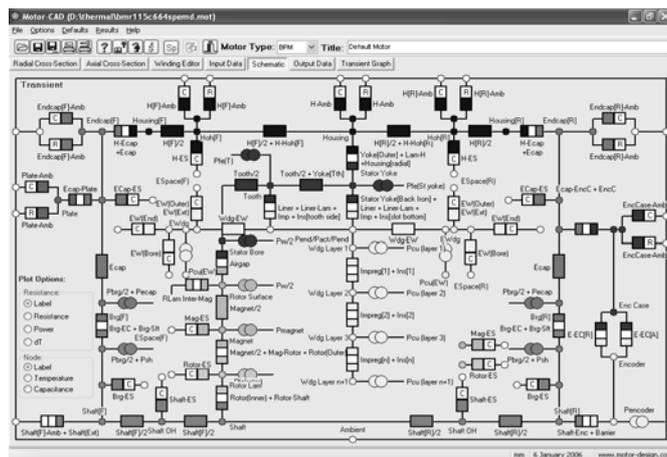
Fig. 8: Motor-CAD thermal model

4.3 Results and comparison with experimental

The transient response of the Motor-CAD simulation is shown in Fig. 9. This shows a reasonable correlation to the measured data. Table 1 summarises the steady-state results.

Fig. 10 compares the measured and calculated winding and endcap temperatures. The correlation is excellent.
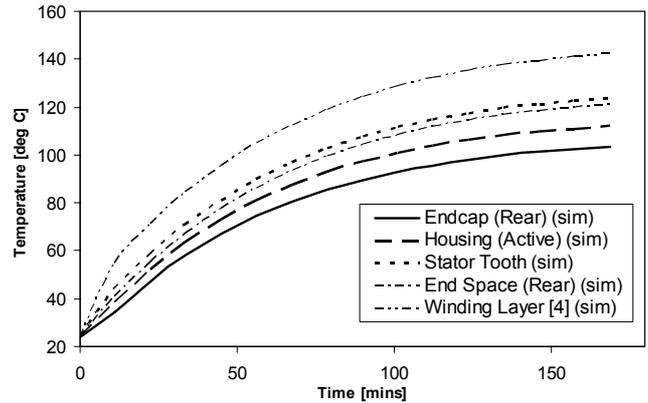
Fig. 9: Transient thermal run-up simulation

Temp location	Measured (deg C)	Simulated (deg C)	Error (%)
WindingLayer	144.3	148.1	2.6
Housing	117	117	0.0
Tooth	127.9	129.4	1.0
End Winding/space	134.1	126.8	-5.5
End Cap	107.4	107.9	0.5

Table 1: Comparison between measured and simulated steady-state temperatures
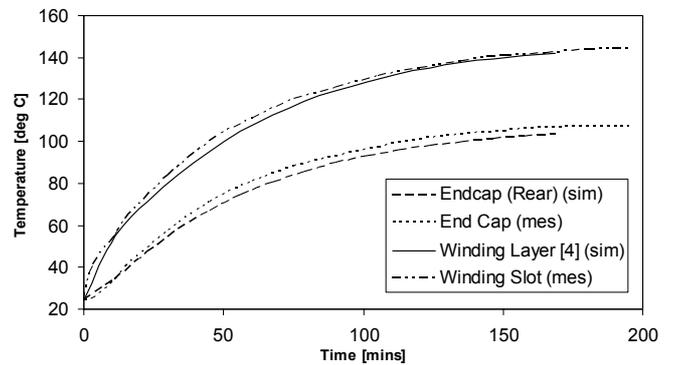
Fig. 10: Comparison between measured and simulated transient thermal run-up

Fig. 11 shows the duty cycling variation. Compared to Fig. 6 the correlation is good except for the shaft temperature. Direct comparisons are shown in Fig. 12. These are very good except for the shaft measurement – although the trend shape is correct. This measurement was taken with a hand-held thermometer and it is assumed that it may well have been reading low or the results incorrectly taken.

4.3 Verification of thermal rating and effects of mounting

The machine has F Class thermal rating which specifies a maximum temperature of 155 ºC and an ambient temperature up to 40 ºC. Therefore we can set the ambient to the maximum value to find the steady-state temperature to validate the thermal rating. If we do this we get a peak temperature in the winding of 162.1 ºC. This is above the

rating. However, the mounting for this machine is not very substantial. If we increase the flange plate from 140 mm square to 300 mm square then the winding temperature now drops to 150.4 ºC, which is within the thermal rating. This illustrates that the machine mounting has a great influence on the temperature of the machine.
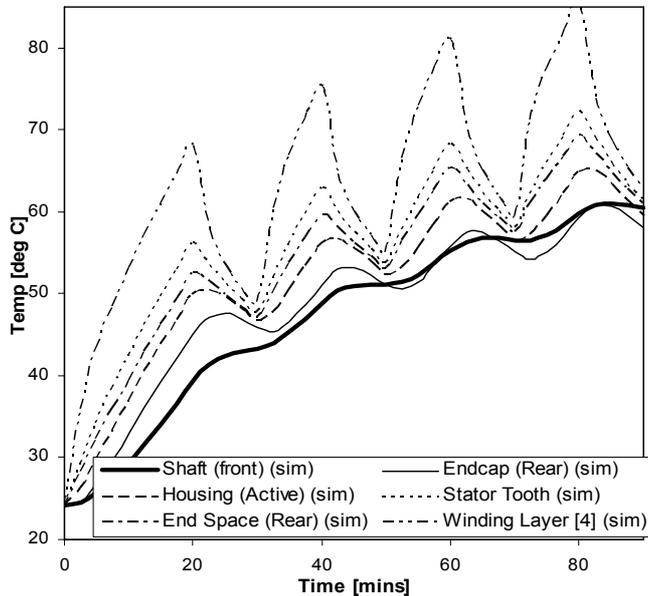
Fig. 11: Duty cycling simulation
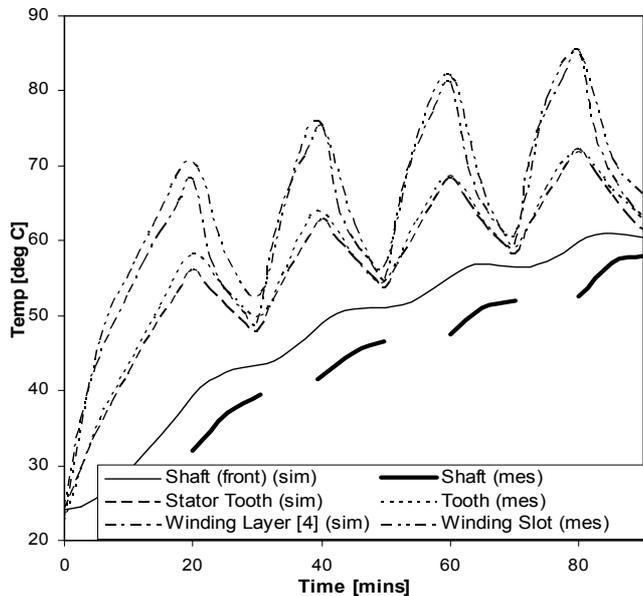
Fig. 12: Comparison between measured and simulated duty cycling

4.4 SPEED thermal model

PC-BDC contains several thermal models of varying complexity. The simplest models allow the designer to carry out machine sizing based on the input of a few parameters gained from previous experience, i.e. motor thermal resistance, housing heat transfer coefficient, etc. The most complex model is a 10 node network of the machine representing:

- End Winding
- Stator Conductor
- Stator Bore
- Airgap
- Rotor
- Frame
- Shaft
- Stator Teeth
- Stator Yoke
- Bearing

This can be tuned using structural and manufacturing parameters to give a thermal transient calculation. This requires some intuitive knowledge of the thermal network and space constrains prevents further study of this here.

5 Conclusions

This paper gives the details of a thermal study of a brushless servo motor and shows how this can be simulated using a combination of an electromagnetic package (to obtain the correct electromechanical operation and loss data) and a thermal package (to obtain a detailed thermal analysis). The method demonstrates that it is possible to obtain reasonable results and it illustrates that it can be used to assess the effects of design changes and validate insulation systems. Further ActiveX scripting can improve the transient analysis data linkage. This illustrates the flexibility of ActiveX facility in Windows-based software packages.

Further work will be to investigate machines with more complicated thermal requirements and networks such as the induction motor.

Acknowledgements

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