Motor-CAD Software for Thermal Analysis of Electrical Motors - Links to Electromagnetic and Drive Simulation Models

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Abstract- Motor-CAD software is the unique software for the analytical lumped circuit thermal network analysis of electric motors. Motor-CAD is used by many of the most successful motor manufacturers to optimise the cooling of various motor types and cooling methods. At INDUCTICA 2009, Motor Design Ltd (MDL) presented a paper explaining the development of the Motor-CAD software, detailing the mathematics involved and giving examples of the software in use. This presentation gives details of work done to create automated links from Motor-CAD to other commercial software packages that are used to model the electromagnetic and electronic drive design, e.g. SPEED, FLUX and PORTUNUS. Using the new multi-physics environment it is possible to obtain a better optimum design than could be achieved by just considering the electromagnetic, thermal or drive design in isolation. For instance, the dependence of losses on temperature and temperature on losses are discussed in detail, as is the importance of accurate predictions of the magnitude and distribution of magnet and winding proximity losses on temperature estimation.

Introduction:

When optimising a motor design there is a fine balance between simulation model accuracy and calculation time. The optimum solution will only be found if a satisfactory number of designs can be performed in the time available and that the model accuracy is sufficient to give reliable results. Accurate multi-physics calculations are required for the magnetic, electrical, thermal and mechanical criteria. In terms of software tools available, one extreme would be to use a 3d FEA electromagnetic model to calculate the motors magnetic circuit, with the winding fed by a full drive model and the thermal performance calculated using a 3d CFD model with losses coming from the 3d FEA model. This would have such a long execution time that it would be impossible to calculate anything other than the performance of a design that already exists. The other extreme is to have a full set of analytical models for the electromagnetic design, drive and cooling system. This gives fast calculation speeds, but can have limitations on the complexity of the geometries modelled, e.g. exact electromagnetic or thermal formulations may not be available for very complex geometric parts and/or they may not have sufficient accuracy that the results are reliable. In such cases it is useful to make numerical FEA or CFD calculations and/or tests on actual machines and make adjustments to the analytical formulations to give better accuracy. This calibration process is illustrated in Fig 1.
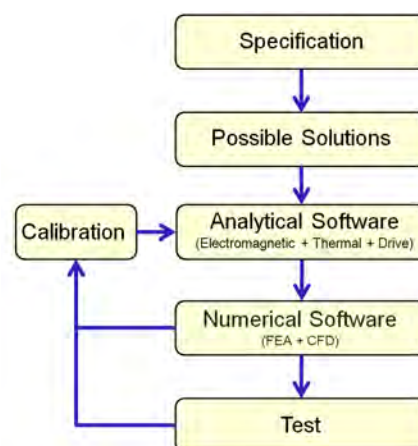

Fig 1: The motor design process, including calibration to give increased analytical model accuracy

The calibration process can be very time consuming and so it can be tempting to dispense with it when a fast design turnaround is required. In such cases there is a real risk that the design will be far from optimum and in some cases may not achieve the desired performance. To allow the calibration process to be used more often, MDL have developed methods to automatically transfer geometry, material data, etc from the analytical models to the numerical models, run the numerical models, carry out post processing and feed the required calibration data back to the analytical models. Some of these automation methods are described in this paper, with an emphasis on the links between the Motor-CAD thermal analysis software developed by MDL with SPEED, FLUX and PORTUNUS.

SPEED is an analytical algorithm based software used to calculate the performance of different types of electric motor, e.g. brushless permanent magnet (BPM), induction, switched reluctance, etc. Many multi-physics calculations are performed in SPEED. For instance, in order to calculate the performance of a BPM machine, PC-BDC calculates the magnetic circuit, the winding resistance and inductance, the current from the drive, the torque produced by the interaction of the winding current and permanent magnet field, the losses in the machine, etc. SPEED does include a simple thermal model to predict the temperature of the winding and magnets as these are important considerations to allow an accurate calculation of the electromagnetic performance, i.e. the magnet flux reduces when hot leading to a requirement for an increase in current to maintain the same level of torque, and the winding resistance rises with temperature so causing an increase in copper losses. The main problem is that the SPEED thermal model lacks sophistication and relies on the user to input data from their own experience or from a more accurate thermal model. To overcome these limitations we have developed automated calls to the Motor-CAD software to calibrate the SPEED thermal model. SPEED also has some limitation in terms of accuracy of some of the more complex loss mechanisms, e.g. magnet loss and winding proximity loss. To help overcome these difficulties we have developed automated links from Motor-CAD to FLUX FEA software. Data from FLUX can then be used to calibrate the Motor-CAD and SPEED models. This paper gives details of the links between Motor-CAD and SPEED for thermal model calibration and from Motor-CAD to FLUX for magnet and winding proximity loss calibration.

Automated calls are also available from Motor-CAD to FLUX to make 2d thermal FEA solutions that can help calibrate the analytical thermal conduction networks used for complex composite components such as the conductors in a slot. An example of a form wound winding is detailed in the paper. When we wish to investigate a particular motor design operating with various load cycles and various drives control/switching strategies, it is often advantageous to use simplified electromagnetic and thermal models in a mechatronics system simulation environment such a PORTUNUS. The important thing here is that the electromagnetic and thermal models have the same characteristics as the more complex full models used in the SPEED and Motor-CAD design environments. This paper gives brief details of a reduced nodal thermal network that is automatically created in PORTUNUS when we import a Motor-CAD model. The reduced nodal network has the same transient thermal response as the full network.

Motor-CAD Software:

Motor-CAD is a unique software dedicated to thermal analysis of electrical motors and generators. It is based on network (lumped circuit) analysis. Nodes are automatically placed at important points on the motor cross-section, such as the stator back iron, tooth, winding hotspot, etc. These are linked with the conduction, convection and radiation thermal resistances. Losses are input at the relevant nodes. Thermal capacitances are added when thermal transient analysis is performed. Fig 2(a) shows a typical thermal network constructed by the software. Fig 2(b) shows a typical thermal transient calculated by Motor-CAD, in this case for a complex duty cycle load. The experience of the Motor-CAD development team and the backup given from its links with universities and industry has been used to make sure that this network gives an accurate representation of all the important heat transfer paths in the machine. More details regarding Motor-CAD are given in [1,2].
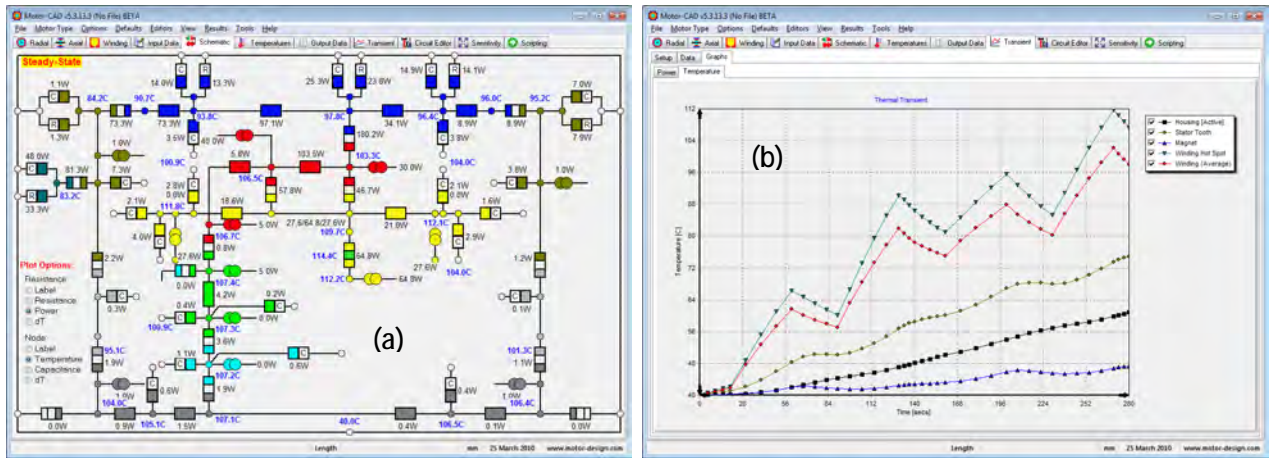
Fig 2: Motor-CAD Steady-State Schematic Diagram and Thermal Transient Graph

Motor-CAD Links to SPEED Software:

To obtain a true optimum design it is essential to take account of both the electromagnetic and thermal design aspects. In fact there should be strong interaction between the two disciplines as it is not possible to accurately analyse one without the other, i.e. the losses are critically dependent upon the temperature and vice versa. Various automated data links have been developed between SPEED and Motor-CAD software. The two packages form a perfect combination for designing electric motors and generators. The thermal capabilities of Motor-CAD ideally complement the electromagnetic capabilities of the SPEED software. Geometry, winding, losses and temperature data can be automatically transferred between the programs as illustrated in Fig 3.
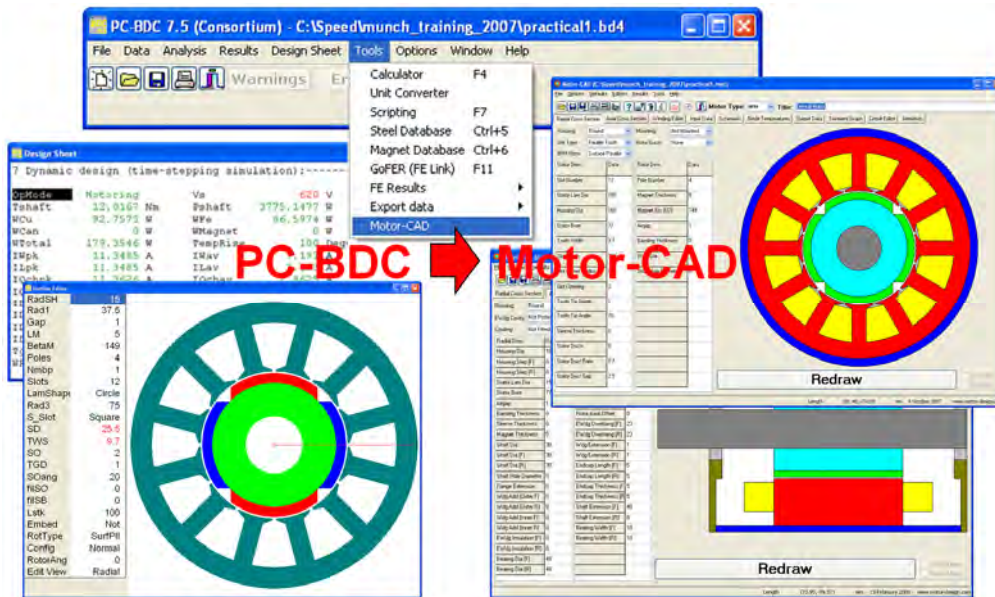

Fig 3: Automated transfer of data from SPEED to Motor-CAD

The SPEED software also has some of its own very basic thermal models, ranging from a single thermal resistance from winding to ambient to a more useful model with a few resistances from winding to housing, housing to ambient and stator to rotor. The Motor-CAD thermal model can now automatically calibrate the simplified SPEED thermal models, such that the user can more accurately calculate the electromagnetic performance and only need to recalibrate when changes are made to the design. This powerful calibration process is referred to as a GoTAR, which stands for **Go T**hermal **A**nalysis and **R**eturn. There is another calibration process available in SPEED called a GoFER (**Go F**inite **E**lement analysis and **R**eturn). The GoFER is used to calibrate some of the analytical electromagnetic calculations in SPEED using its own integrated magneto-static finite element program called PC-FEA. The typical GoTAR process is illustrate in Fig 4. In this case the

nodal temperatures and heat transfer predicted in the Motor-CAD thirty or more node model are used to automatically calibrate the thermal resistances in the PC-BDC four node circuit. The process is iterative due to non-linear such convection, radiation and loss variation with temperature.

In Motor-CAD the user can change thermal parameters such as cooling type, housing type, insulation materials and dimensions, etc. Motor-CAD also has built in sophisticated algorithms to model how losses vary with temperature and load. The data used to calibrate this model is taken directly from PC-BDC. This model accounts for the loss in flux from the magnets as they heat up (modelled using the temperature coefficient of remanance for the magnets) requiring a larger current to obtain the required torque. It also accounts for the increase in winding resistance with winding temperature and the resulting increase in copper loss. This model is very useful for accurate modelling of thermal transients, as the losses increase with time even if the torque or current for the machine are kept constant.
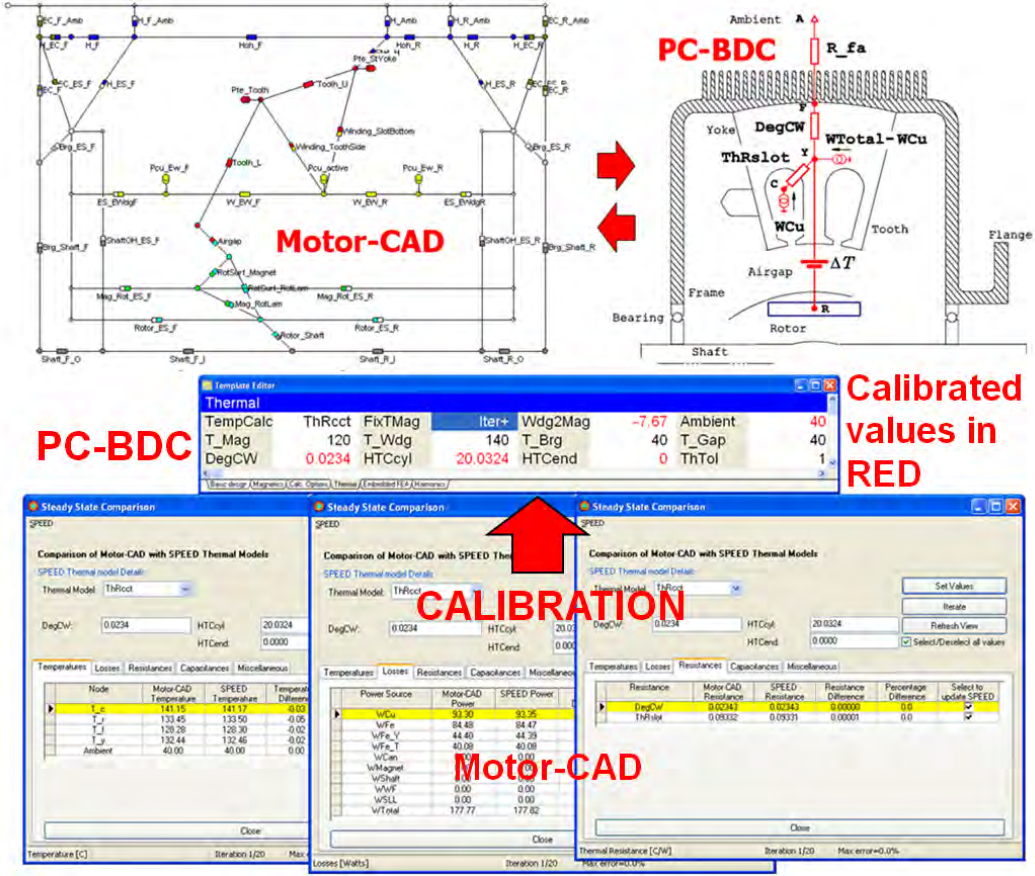

Fig 4: SPEED/Motor-CAD GoTAR process to automatically calibrate the SPEED simplified thermal model using the more sophisticated Motor-CAD model

Motor-CAD Links to FLUX FEA Software:

Several automated links have been created from Motor-CAD to the FLUX finite element software. Some of the links are for calibration of certain thermal conduction paths in the Motor-CAD model and some are to make an accurate calculation of certain difficult to calculate losses and feed these into the thermal model, e.g. calculation of magnet and winding proximity losses which are difficult to calculate accurately using analytical methods. This paper gives a brief description of the following Motor-CAD to FLUX links:

- Calibration of the form wound winding model using a FLUX thermal conduction model
- Calculation of magnet and winding proximity losses

Calibration of the form wound winding model using a FLUX thermal conduction model:

The Motor-CAD layered winding model was originally developed to model the temperature rise in a random wound stranded conductor winding. In Fig 5(a) we see the actual strands of wire in the slot. In Fig 5(b) we see a set of material layers set up from slot wall to slot centre, the dark green being the slot liner, yellow copper, light green impregnation/air mix and purple enamel. The layers start at the slot boundary with the slot liner (known thickness) and then layers of impregnation, wire insulation and copper. The amount of each material in layered model is made equal to the known material amount in the actual slot. Each layers thermal resistance is calculated from the layer thickness (l), layer periphery multiplied by stack length (A) and layer material thermal conductivity (k), i.e. R = l/(kA). The winding thermal resistance network for the layers is shown in Fig 5(c). Copper loss is injected into the copper layers according to the layer cross-sectional area. The layered winding model is used to calculate the temperature rise from slot wall to winding hotspot at the centre of the slot. We have done extensive finite element analysis, such as that shown in Fig 6, to confirm that the layered winding model gives reliable results.
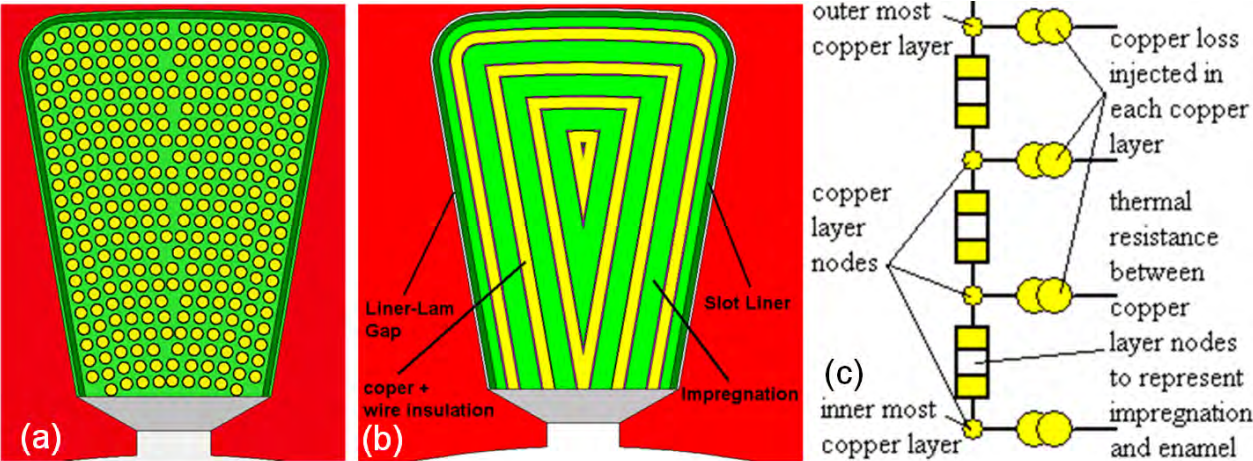

Fig. 5: Layered winding model to calculate temperature rise in a stranded random wound winding
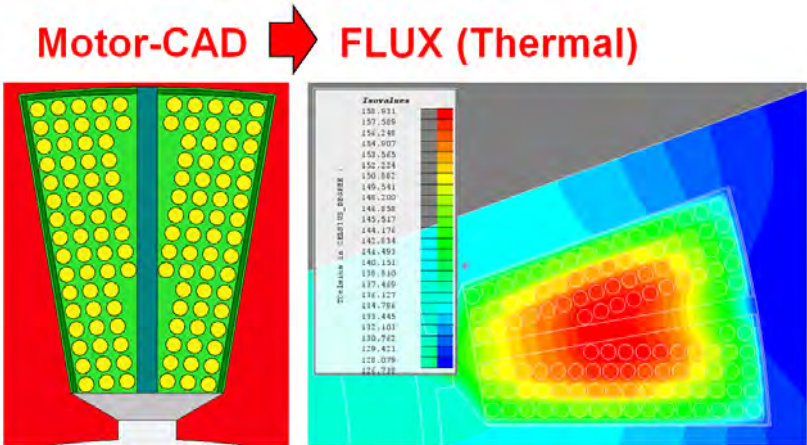

Fig 6: Motor-CAD stranded conductor random wound winding thermal resistance calibration

The layered winding model thermal resistance network accurately matches the heat transfer path for the stranded winding as the hotspot is usually at the centre of the slot and heat transfer is in a direction perpendicular to the slot wall. The network is not however suited to the form wound winding as shown in Fig 7. Here we have the rectangular conductors placed down the length of a slot giving a dominant temperature rise from slot bottom to a hotspot towards the stator bore. It is possible to model conduction heat transfer through the winding and resulting temperature

distribution quite accurately for this type of winding using FEA. This is because we have more knowledge of the conductor and insulation position than in the random wound machine. We have experimented with various complex thermal resistance networks to attempt to give an accurate calculation of the winding temperature distribution. It was decided that a very simple two node circuit within the winding is best to predict the winding average winding temperature, i.e. a node at the centre of the upper slot coil and node at the centre of the lower coil. This gives a very fast calculation, which is important for complex transient duty cycle calculations. An automated Motor-CAD to FLUX calibration process has been developed and is illustrated in Fig 7. While the calibration process is useful it is not essential as the mathematics inbuilt into Motor-CAD to calculate the interconnection of the two winding nodes with the remainder of the circuit is developed to be as accurate as possible without calibration. The calibration process gives the benefit of an estimate of the difference between minimum, maximum and average winding temperatures. In the calibration, end effects are turned off in Motor-CAD to match the 2d FEA solution. Equal losses are put into both models and a fixed stator outer surface temperature set.
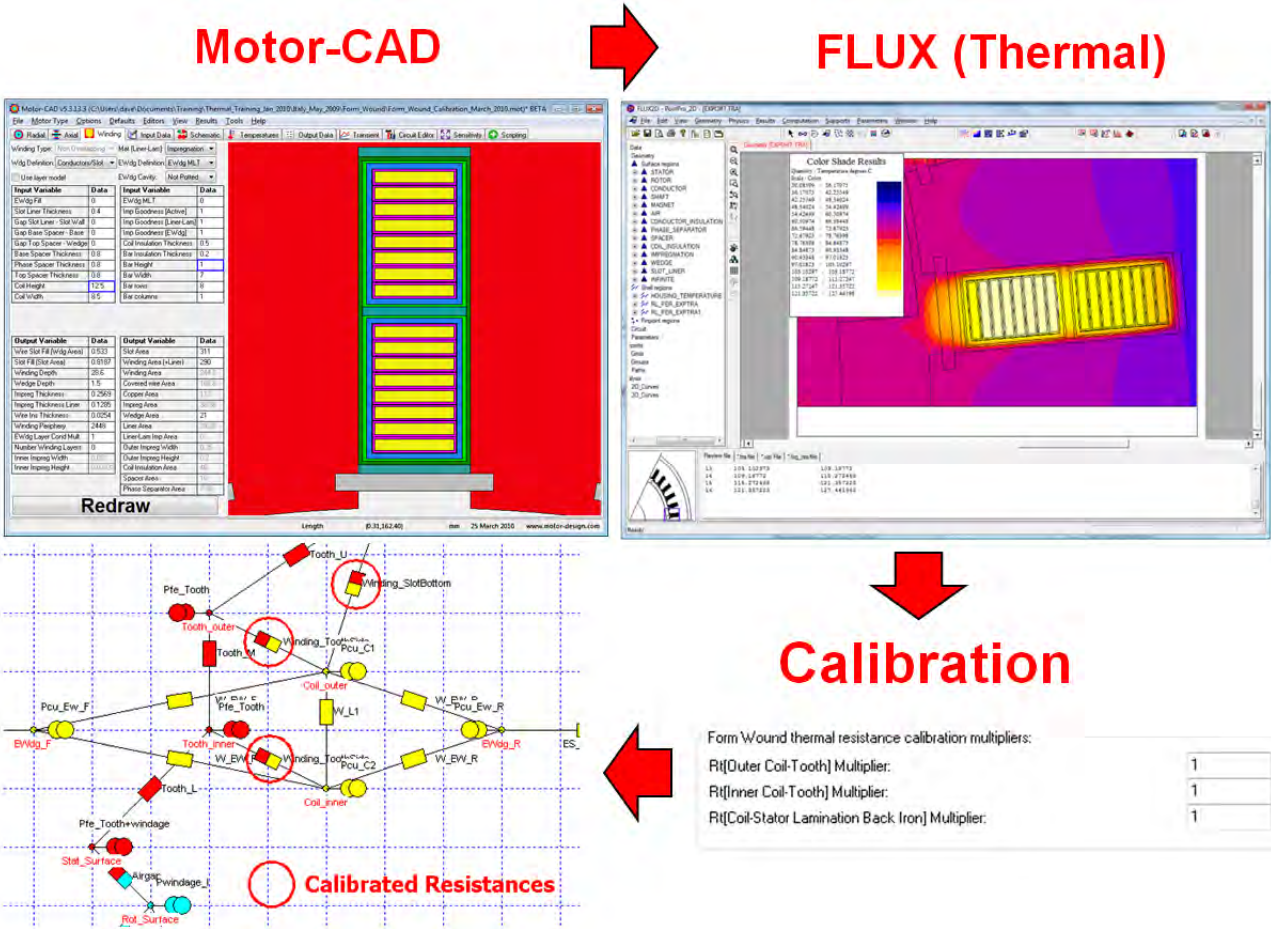

Fig 7: Motor-CAD form wound winding thermal resistance calibration using FLUX thermal FEA

Calculation of complex loss mechanism such as magnet and winding proximity losses:

As new BPM motor designs become more compact and run at higher speeds it is no longer possible to ignore losses such as magnet [3] and winding proximity [4] losses. The FEA method is ideally suited to make an accurate calculation of such losses. This involves the calculation of eddy currents induced within the magnets or winding conductors. To do this we need to create an FEA model that describes the motor cross-section including the magnet segments and individual wires in the

winding. These parts are modelled as solid conductors with a circuit attached to allow the calculation of the currents induced within them. A transient magnetic calculation is performed. In Figs 8 and 9 we see typical FLUX model results for magnet and winding proximity losses. In both cases the geometry, materials, boundary conditions and electrical circuit created in FLUX are automatically set up from Motor-CAD. If the calculation were not automate, it could take several hours to set up a model, especially if there are many conductors and/or many magnet segments and if the motor geometry is quite complex. This could limit the use of such calculations. With the automation the calculation is a simple process taking a few minutes and is more likely to be used in the design process and lead to better designs.
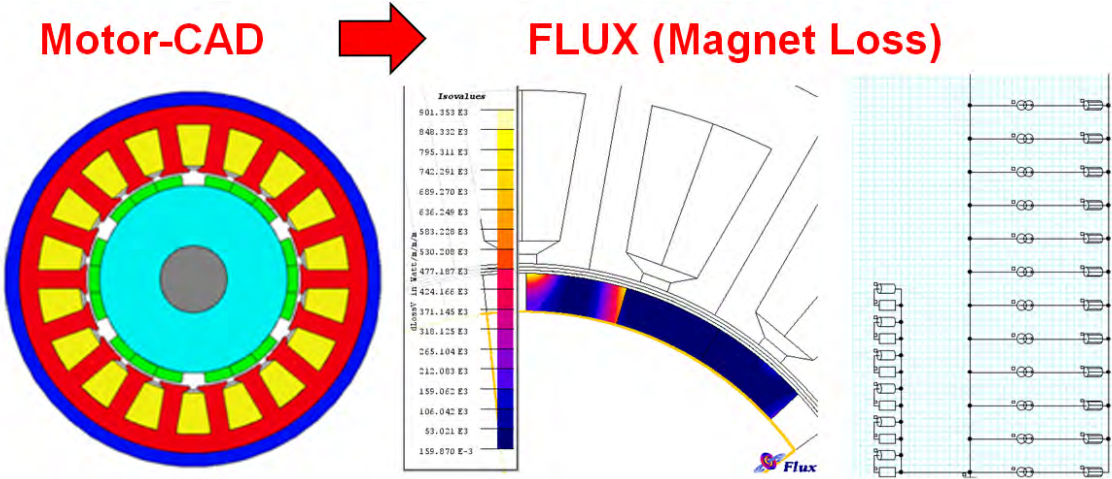

Fig 8: Motor-CAD links to FLUX to automatically calculate magnet losses
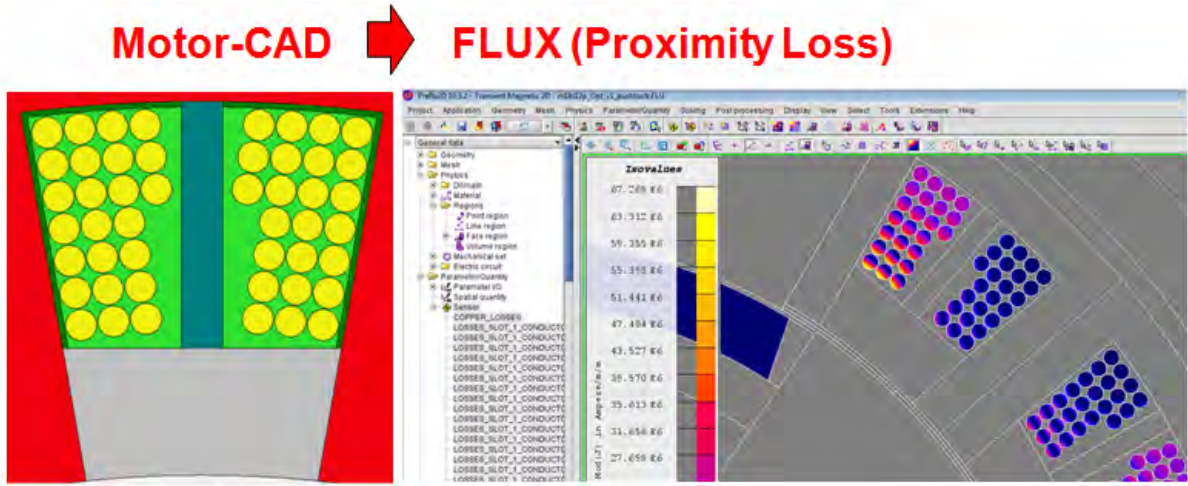

Fig 9: Motor-CAD links to FLUX to automatically calculate winding proximity losses

Motor-CAD Links to PORTUNUS System Simulation Software:

PORTUNUS is a system simulation software that is ideally suited to multi-physics mechatronic calculations. For instance in Fig 10 we see a model for a line fed 3-phase induction motor where we model the transient start up taking full account of non linear magnetic and thermal effects on the performance. The motor non-linear electromagnetic equivalent circuit model estimates the losses produced, with an iterative link to a thermal model to account for temperature rise with time. In this case the non-linear equivalent circuit model, which accounts for saturation and non-linear iron loss effects, was developed by MDL and implemented using the open VHDL-AMS language interface to PORTUNUS. The model is set up either by parameters gained from no-load, load and locked-

rotor measurements or from SPEED PC-BDC and/or FLUX model results. Rather than use the full 30+ node Motor-CAD thermal network in the PORTUNUS model, we use a reduced nodal network that has the same transient thermal response. Seven nodes are used in this simpler thermal model. The reduced nodal model is automatically created in Motor-CAD and imported into the PORTUNUS model. Nodes are available in the reduced nodal model to allow connection to a thermal network to represent the cooling of the equipment within which the motor is built. The reduced nodal network has the advantage of less data to transfer and faster simulation times.
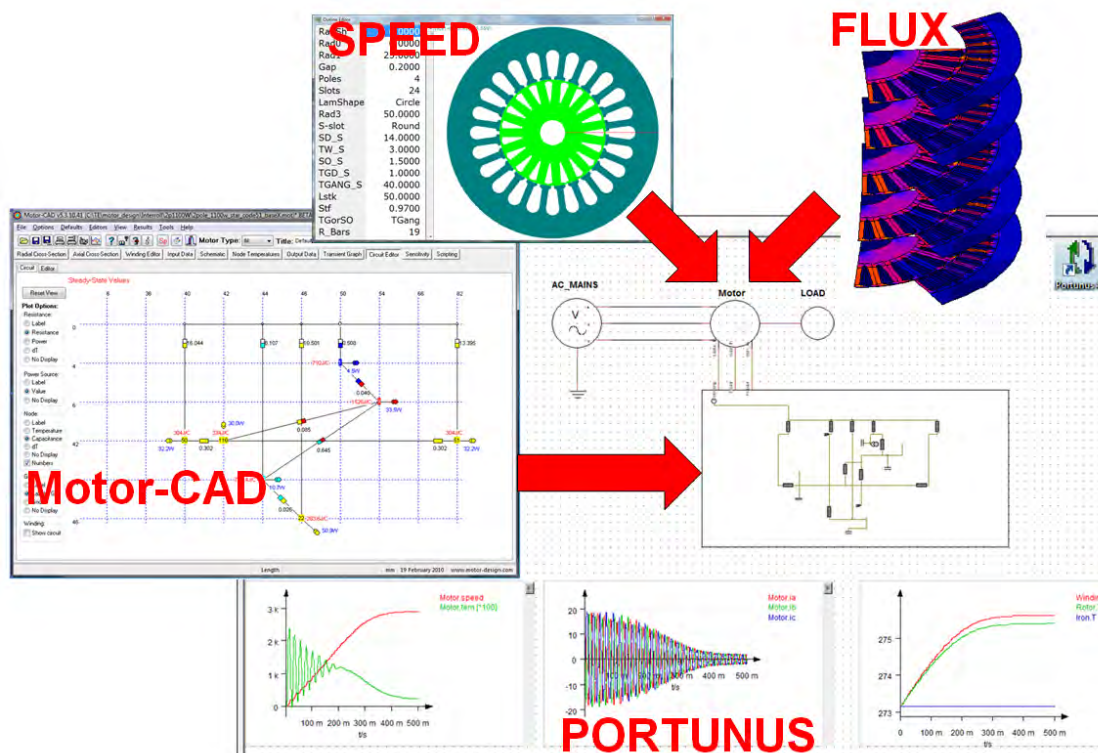

Fig 10: Motor-CAD, SPEED & FLUX link to PORTUNUS to make multi-physics system simulation

Conclusions:

This paper reviews some of the automated links that have been developed between Motor-CAD, SPEED, FLUX and PORTUNUS. These allow calibration of simpler analytical models using more complex analytical and/or numerical models. Multi-physics calculations with higher accuracy and faster calculation times are now possible. The improved accuracy and speed also facilitates reliable design optimisation. The automated links between models in the different software packages make data transfer much easier than was previously possible and it is now more likely that such model calibration techniques and improved accuracy calculations be used in the design process, leading to optimised designs.

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