Coupling Thermal and Electromagnetic Analysis Software

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In this paper we will mainly be looking at the techniques used and advantages gained from coupling analytical packages for electromagnetic and thermal analysis of electric machines. Much of the information will be particular to the commercially available *SPEED*[1] and *Motor-CAD*[2] packages. The techniques can however be applied to other analytical based packages. We will also concentrate on brushless permanent magnet motor design here but packages are available and the coupling techniques are applicable to other motor types.

The *SPEED* and *Motor-CAD* 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. 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 impossible to accurately analyse one without the other, i.e. the losses are critically dependent upon the temperature and vice versa. The combination of *SPEED* and *Motor-CAD* is now even easier to use as it is now possible to automatically transfer data between the two packages.

The data transfer is carried out using ActiveX links – this is a standard technique used in Windows® to pass data between packages.

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[1] *SPEED* software is from the University of Glasgow *SPEED* Laboratory
[2] *Motor-CAD* is from Motor Design Ltd

Motor-CAD and SPEED software

Both *SPEED* and *Motor-CAD* have analytically based algorithms that allow near instantaneous calculation speeds and make possible "what-if" scenario calculations in real time. Their sophisticated user interfaces are designed such that input parameters can be effortlessly changed and their effects on the design easily viewed using dedicated output diagrams, graphs and design sheets. The ease of use of the software allows even non motor design experts to be up and running, calculating valid designs in a relatively short time. They also make excellent teaching tools as the user can vary parameters and examine their effects on the performance.

Motor-CAD links to SPEED:

Geometry and losses can be passed from *SPEED* to *Motor-CAD* and temperatures and geometry back. The data transfer is carried out using ActiveX links. The dialog box that controls the data that is to be imported from *SPEED* and exported from *Motor-CAD* is shown in Fig 1. The user can select the amount of data that is to be imported and exported using the check boxes provided. An option is provided in the dialog to iterate to a converged solution. When activated an automatic iterative loop is performed where the *SPEED* losses are imported and the *Motor-CAD* temperatures exported until convergence is obtained (losses

dependent upon temperature and vice versa). In order to be able to transfer data between two files they just need to have the same name before the .bd4 and .mot extensions and be in the same folder.
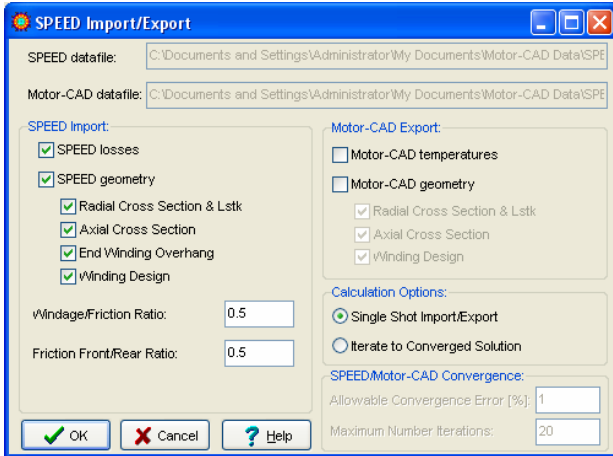

Fig 1: Import/Export Dialog

ActiveX

The data transfer is carried out using ActiveX links – this is a standard technique used in Windows® to pass data between packages. Commands such as those shown below can be accessed remotely from the two programs:

- SetParameter(Par_Name,Par_Value)
- GetParameter(Par_Name,Par_Value)
- DoSteadyStateAnalysis
- DoTransientAnalysis
- LoadFromFile(File_Name)
- SaveToFile(File_Name)

These commands are used to automate the transfer between the two programs. Additionally both *Motor-CAD* and *SPEED* can be fully automated and run from any ActiveX enabled software such as Excel, Matlab, C++, Python, etc. This allows the user to combine either of the packages into their own design environment, automatically passing any relevant data between the users code and *Motor-CAD* and/or *SPEED*. Also the user can easily write automated optimisation and sensitivity analysis routines.

Motor Cross-Section

In *SPEED* the user inputs the geometry using a dedicated radial cross-section editor as shown in

Fig 2. This includes just the electromagnetic components as it is these that are import for the performance. In *Motor-CAD* the user has a similar radial cross section editor as shown in Fig 3. There are however extra components added such as the housing as there are important in calculating the thermal performance. For thermal analysis the 3-dimensional nature of the machine must be defined so an axial cross section editor is provided as shown in Fig 4. Much of the geometry can be imported directly from the *SPEED* software. The user then just needs to set a few additional geometric parameters that describe the housing, bearing and details such as gaps around the end-winding, etc. The visual feedback helps the user to make decisions as to if the design looks valid and to spot errors made when changing geometric data.
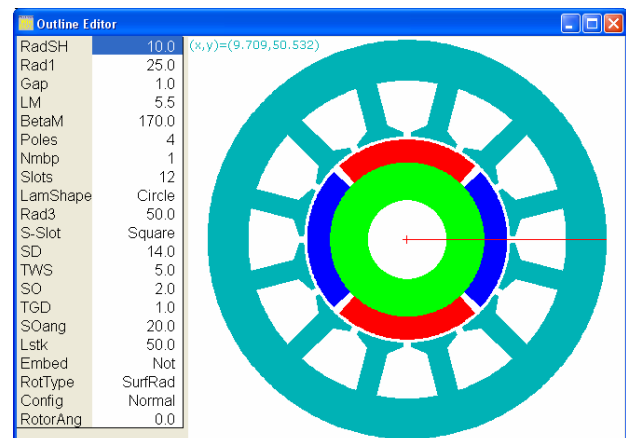

Fig 2: PC-BDC cross-section editor

Winding

The position of the conductors is important in the electromagnetic design and an editor is provided to place conductors as shown in Fig 5. For the thermal analysis the distribution of copper and insulation in the slots is important. An editor is available that indicates the general position of the slot liner, copper and impregnation/air is shown in Fig 6. This is in the form of layers of the different conductivity materials. The amount of copper and insulation in the *Motor-CAD* thermal model is equivalent to that in the *SPEED* electromagnetic model. The number of turns/slot, wire size and mean length per turn can be transferred automatically

between programs. The layered winding model allows the calculation of thermal resistances from the hot spot at the centre of the winding to the cooler sections of the winding at the lamination boundary (Fig 7), i.e. $R = l/(kA)$ where R is layer thermal resistance, l the layer length, k the layer thermal conductivity and A the layer area. Copper losses are injected into the copper layers according to the layer volume. The copper loss is imported from *SPEED*.
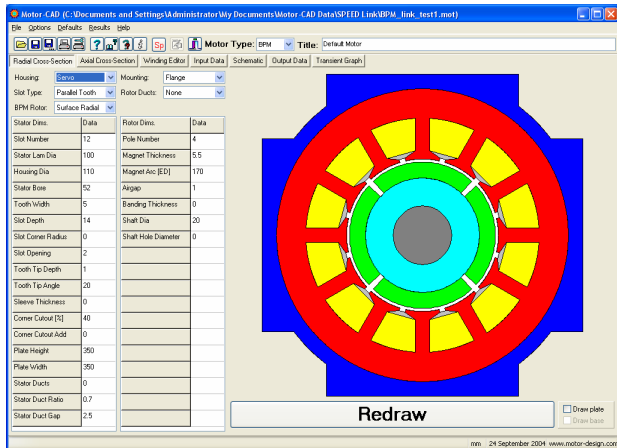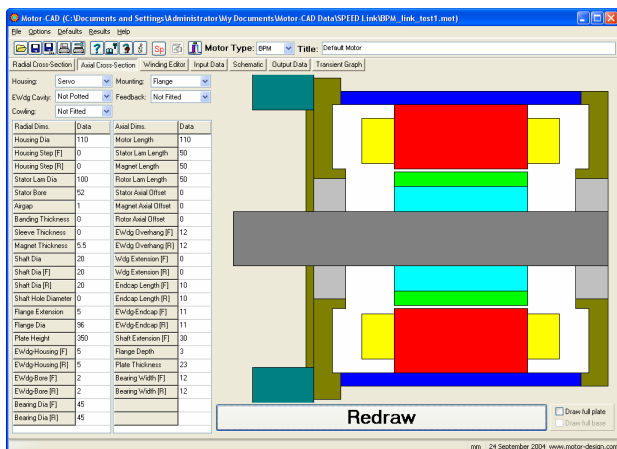

Fig 3: Motor-CAD radial cross-section editor

Fig4: Motor-CAD axial cross-section editor

Materials

In the electromagnetic design the user sets B-H and loss data and selects the drive type (i.e. Sine/Square), etc. In the thermal analysis the user sets material thermal data such as thermal conductivity, specific heat capacity, etc and makes decisions of what cooling types are to be used. A comprehensive set of cooling models are available, i.e. totally enclosed natural

ventilation (TENV), totally enclosed fan cooling (TEFC), drip proof, through ventilation, water jacket, wet rotor and wet stator and spray cooling methods.
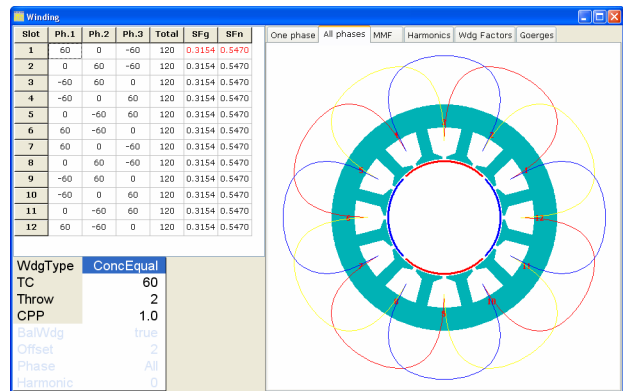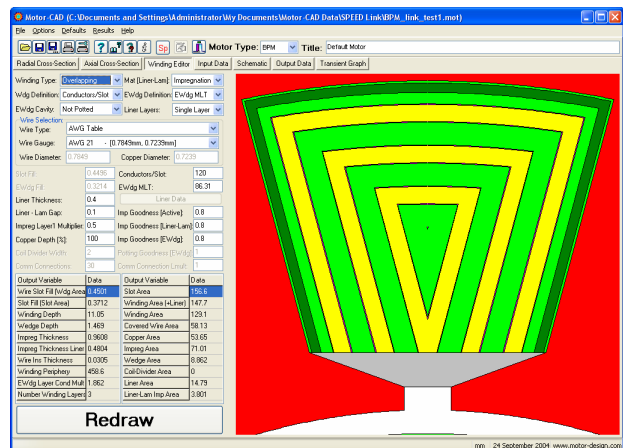

Fig 5: PC-BDC winding editor
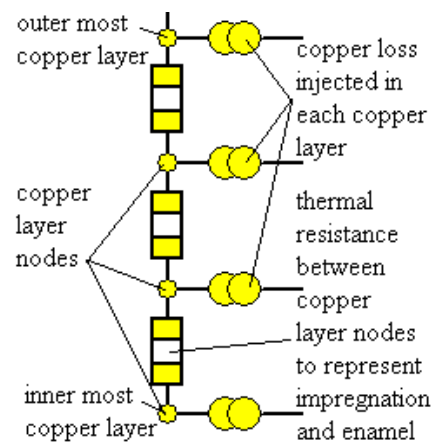

Fig 6: Motor-CAD winding editor

Fig 7: Winding thermal resistances

Losses

For steady-state electromagnetic analysis the user calculates the performance at a given speed and current. Losses will be calculated and can be passed directly from *SPEED* to *Motor-CAD*. In order to accurately estimate the losses the winding and magnet temperatures must be known so these can be passed from *Motor-CAD* to *SPEED*. In fact an iterative solution option is available to make sure that both programs use the same losses and temperatures.

Performance Prediction

In *SPEED* performance characteristics such as those shown in Fig 8 and Fig 9 can be calculated and displayed. For steady-state thermal analysis the schematic diagram is an ideal graphical tool for displaying the temperatures of all components (nodes) within the network and to examine the power flow between nodes (Fig 10). The resistances in the network are colour coded to the components in the cross-section editors. If the user is interested in transient analysis then the required duty cycle load is defined using the graphical editor shown in Fig 11. The thermal transient is then calculated and plotted as shown Fig 12. Fig 12 also shows the excellent agreement with test that can be achieved – in this case measured temperature data for the winding, housing and front flange have been imported into *Motor-CAD* and plotted on the same graph.

Once a thermal model has been created then not only can the temperatures be predicted but more complex details of the thermal design can be examined, e.g. non-perfect impregnation and interfaces between components such as the stator lamination and housing. For such complexities, parameters are provided in the software that that give physical meaning to the phenomena. For instance non-perfect impregnation is modelled as an impregnation goodness factor (e.g. a value of 0.8 means there is 20% air in the impregnation) and will typically have a higher value if vacuum impregnation is used rather than trickle or dip impregnation

techniques. Interface thermal resistances between components are modelled as equivalent airgaps. To assist users set up such parameters, data from practical measurements on real machines are included in the online help. Using *Motor-CAD* it is possible to quickly perform sensitivity analysis and identify all the parameters that have a significant impact on the design such that effort can be concentrated on the most relevant design variables when putting the motor into manufacture. Such sensitivity analysis can be fully automated and run from such packages as Excel or Matlab.
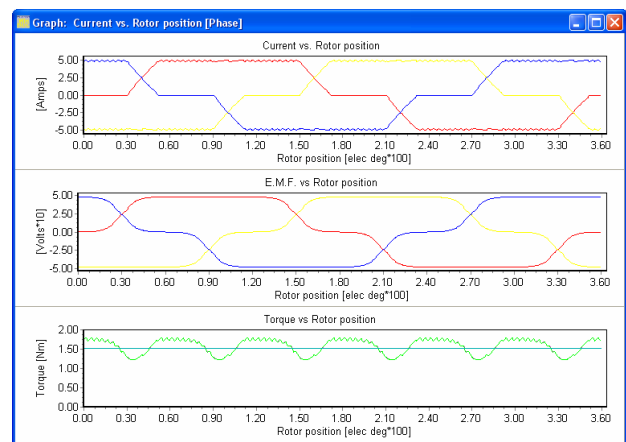

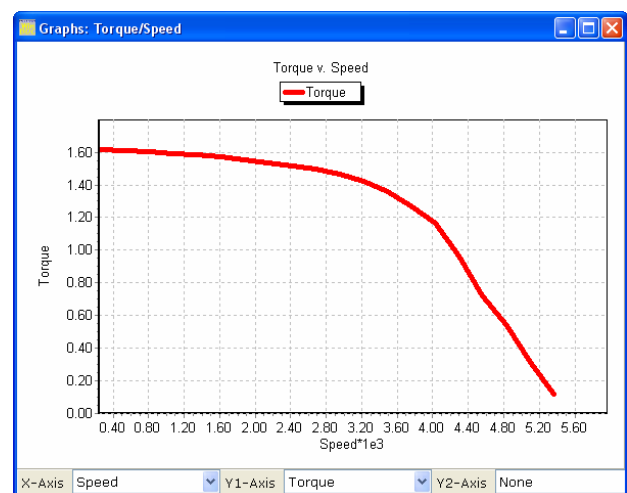Fig 8: PC-BDC steady state prediction
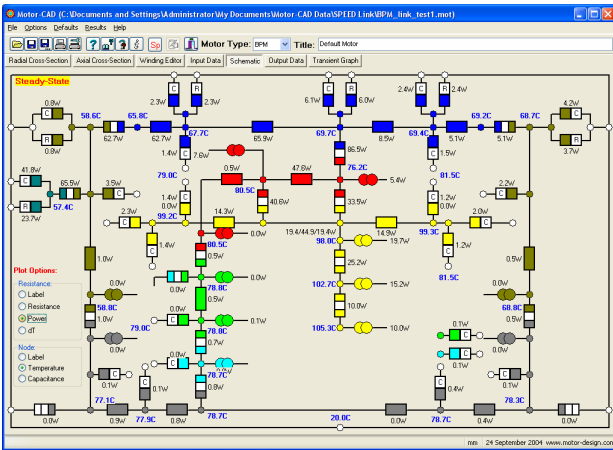

Fig 9: PC-BDC torque-speed prediction

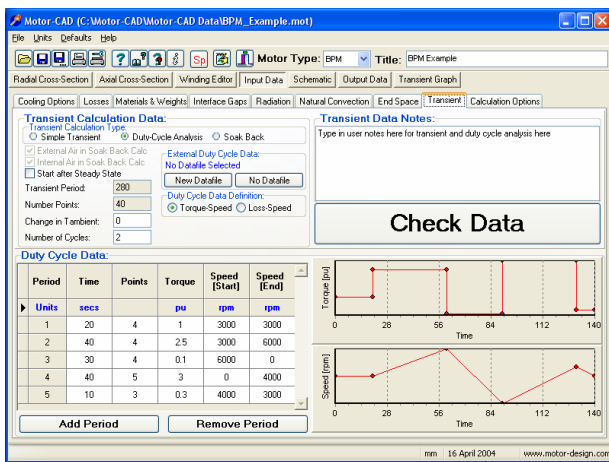Fig 10: Motor-CAD steady-state prediction

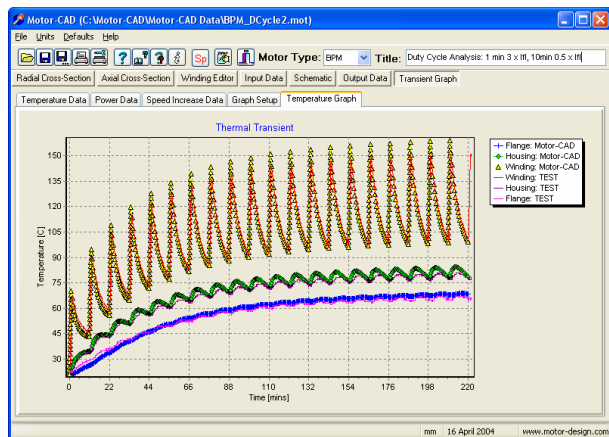Fig 11: Motor-CAD Duty-Cycle Editor

Fig 12: Motor-CAD & measured thermal transient data

Links to other software:

Sensitivity analysis and optimisation routines that call *Motor-CAD* and/or *SPEED* as black-box calculators can be written in any ActiveX enabled programming languages such as Excel-VBA, Matlab, C++, Python, etc. This makes it possible for the user to develop very powerful

packages of their own that automate repetitive calculations. The user can use all the available calls to *Motor-CAD* and *SPEED* such as LoadFromFile, SetVariable, GetVariable, DoSteadyStateAnalysis, DoTransientAnalysis. An example of a simple sensitivity analysis routine that calls *Motor-CAD* to optimise the fin spacing in a particular design is shown in Fig 13. Much more complex routines involving genetic algorithms and transient thermal analysis are possible. Examples will be demonstrated at the seminar.
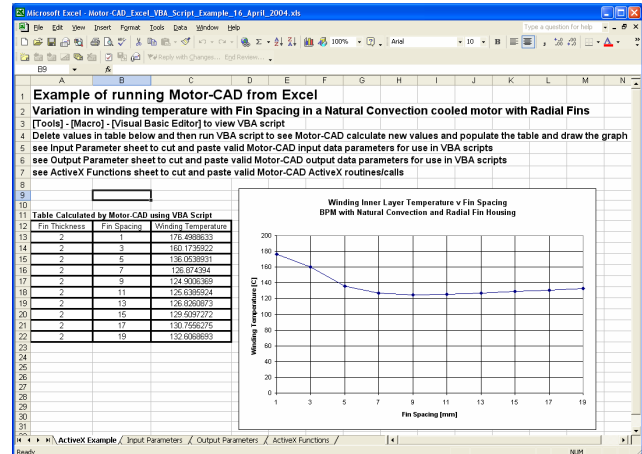

Fig 13: Radial fin spacing optimisation routine in Excel

Conclusions:

The use of Windows® ActiveX technology allows software packages to run as black box applications and allows automated transfer of data between packages. This is very useful for analytically based programs such as *SPEED* and *Motor-CAD* as they work with parameters such as "Tooth Width", "Slot Depth", "Copper Loss", "Magnet Temperature", etc. The automated data transfer possibilities between *SPEED* and *Motor-CAD* have been demonstrated. This allows the user to account for the fact that losses are a function of temperature and vice versa with as little repetitive manual transfer of data as possible. Carrying out the thermal design iteratively with the electromagnetic design allows the user to get closer to an optimum design than would otherwise be possible. The possibility of linking to other software packages to develop automated design routines has also be demonstrated.