Using analytical approach with finite element analysis for coupling magnetic and thermal analysis for motors

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Abstract:

Thermal analysis is a key factor when designing motors. We propose to link the studies of electromagnetic and thermal aspects in transient application with Finite Element Method (FEM) to represent the thermal state of motor with higher accuracy. As electromagnetic response time is different of thermal response time, an original method is used for extracting average values on one magnetic period of losses (Joule and iron losses), and to use them as input for the transient thermal analysis. So, the temperature in different parts of the motor is extracted, and brought back as input for the next electromagnetic computation. The temperature of stator coil and the temperature of magnet are updated. One key point is that only one slot for the rotor and for the stator is modelled for thermal analysis. The FEM results are compared with thermal analysis carried out with MOTOR-CAD software, 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 Limited (MDL) presented a paper explaining the development of the Motor-CAD software, detailing the mathematics involved and giving examples of the software in use. The rise of temperature is analysed, as well as the steady state temperature. An Interior Permanent Magnet (IPM) motor has been used in order to compare results.

Introduction

Designing motors require fulfilling many constraints: mechanical, thermal, efficiency, price … Among these constraints, the thermal constraints are still not an easy task. Full modelling would involve multi-physics analysis, leading to long time of computation. Different strategies can be applied to tackle this task, requiring some assumptions to simplify the different types of modelling.

Different tools are available, with Computational Fluid Dynamics (CFD) analysis, Finite Element Analysis (FEA) or even the analytic method. To try to get the most advantages of different methods, some couplings were proposed between for instance FEA analysis and analytic analysis [6].

In this paper, we propose a new coupling between two different physical applications involving FEA analysis: electromagnetic and thermal analysis. The originality of the work is to propose to carry out one full electric period. Thanks to that, one can reach electromagnetic steady state for a set of temperatures for the rotor and stator and from there one is able to export the losses in thermal analysis environment.
Then, the temperatures of rotor and stator are then re-imported inside the electromagnetic environment to perform the next step of the electromagnetic computation.

In order to check the results of this method, our results are compared with simulation done with analytic method using the MOTOR-CAD software. In our study, the considered motor corresponds to a hybrid vehicle, of IPM type.

1. Principle of the magnetic and thermal coupling with FEA method

This analysis is using multi-physic feature. Data will be exchanged between electromagnetic analysis and thermal transient analysis. On the electromagnetic part, the resistance of coil is depending on coil temperature. On the rotor part, the remanent flux density is also depending on temperature. When the temperature is increased, then the remanent flux density is decreased.
On thermal side, different types of losses are extracted from the electromagnetic analysis: Joule losses inside coils, iron losses in the stator and rotor and also magnet losses.
A specific procedure allows the exchange of data between electromagnetic and thermal environments.

One key point is that the electromagnetic response time is lower than the thermal response time. For this reason, a direct coupling between electromagnetic transient and thermal transient would lead to huge computation of time.
So, first we propose to reach one full electromagnetic period corresponding to a working point in steady state, and then to extract average losses over one electric period, in order to send it as input for the thermal computations.

The whole process can be summarised in the figure below.

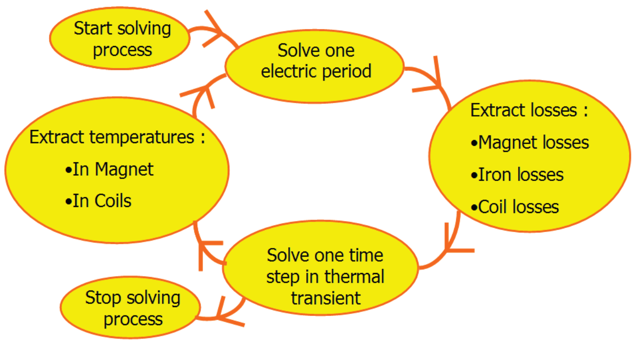

Figure 1: flow chart of the work flow

Another key point is that the represented part is not the same in electromagnetic environment than in thermal environment.
The goal is to save simulation time. On the thermal side, only one slot is represented for stator and only one for the rotor.
But at the same time, this allows us to be much more precise in the way to represent all the components inside the slot and this from a thermal point of view. It means that all the thermal barriers like electric insulation of conductors or coils can be represented.

2. Heating process example on hybrid vehicle

As example, we propose to apply this method to the analysis of an electric motor for hybrid vehicle. The main characteristics of this motor are:
Active power of 50 kW, at 1200-1500 rpm, a peak torque equal to 400 Nm, with a max bus voltage of 500V.
It has 48 stator slots with 3-phased wye connected stator winding. The maximum speed is 6000 rpm. The motor is current driven. The FEM method is applied using Flux software. Due to symmetry only one quarter of the motor is represented. On the figures below isovalues of magnetic flux density and electric circuit are represented.

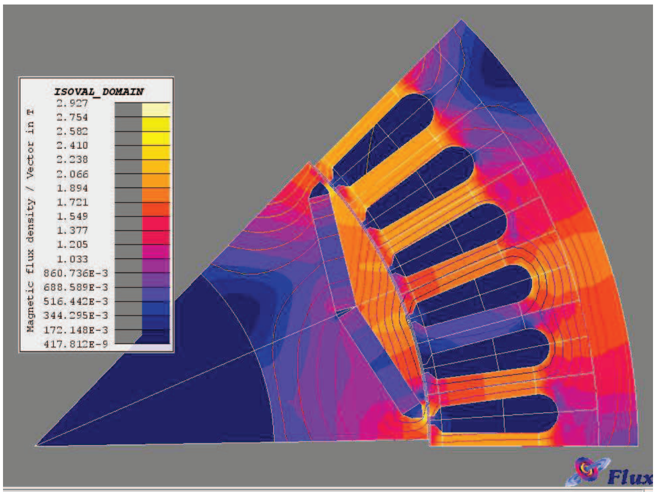

Figure 2: magnetic flux density color shade

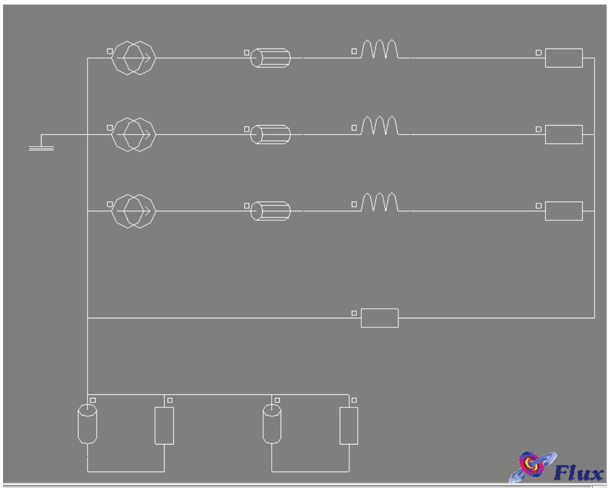

Figure 3: electric circuit linked with Electromagnetic model of the motor

On the magnet side, the resistance of coil is depending on the temperature, as shown on the figure 4., as well as the remanent flux density of magnet. Each magnet is represented in the electrical circuit by a solid conductor in which we assume that the integral of current is equal to zero.

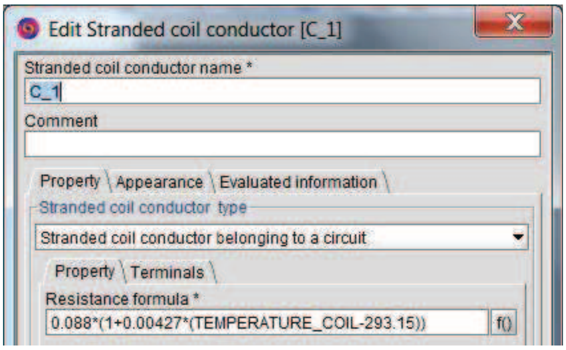

Figure 4: thermal dependence of coil resistance

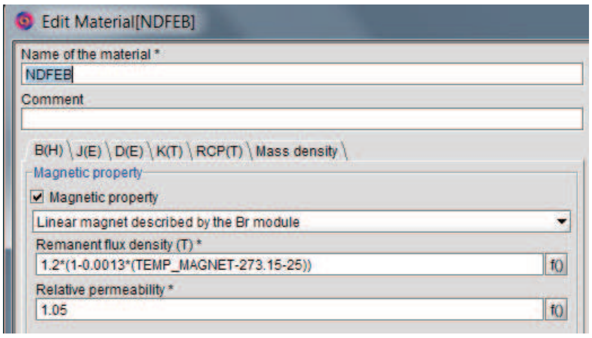

Figure 5: remanent flux density vs. temperature

On the thermal side, two models are prepared: one stator slot, and one rotor slot. The goal is to be able to simplify as much as possible the model, for time of computation, and to still take into account of the maximum details such as coil turns disposal, as well as insulation and liner part (see figure below).

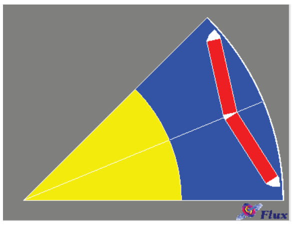

Figure 6: rotor for thermal analysis

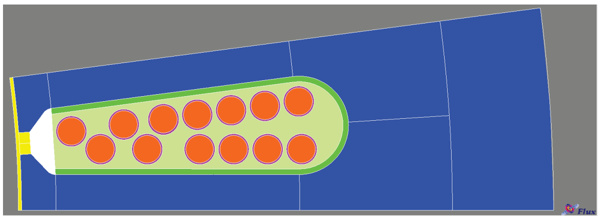

Figure 7: one stator slot for thermal analysis

For thermal boundary, we set the temperature to a fixed value on the external arc of stator. Indeed there is a water jacket cooling system, setting the temperature. For the airgap boundary, we have defined convection and exchange coefficients. At each time step we iterate between rotor and stator analysis in order that the heat coming from the stator is equal to the heat absorbed by the rotor, by modifying the ambient temperature of the airgap. For the radial boundary, we have set cyclic boundary condition.

3. Thermal analysis with analytical method

To carry out this thermal analysis, we propose to use a specific tool called Motor-CAD [5]. With this tool you can describe the geometry with predefined types of motors and predefined slots. You have to define the cross section and also the axial cross section. The next step is to define which materials are used, referring to a list of existing material covering most of typical sheets. Then you define the cooling type (through ventilation, forced ventilation …). You will also need to define the losses (copper, stray losses ...). You have the possibility to define duty cycle of use. In our IPM motor analysis, we propose to use the copper losses, the rotor losses and also the stray losses as input for the thermal analysis. Motor-CAD can carry out static analysis (corresponding to steady state) or transient analysis in order to see the rise of temperature in the different parts of the motor.

Motor-CAD is using an equivalent lumped thermal circuit. Each electrical component is corresponding to some specific thermal resistance. The circuit is determined automatically according to user inputs.

4. First results with thermal analytical analysis

The motor is defined using the cross section editor and the axial editor.

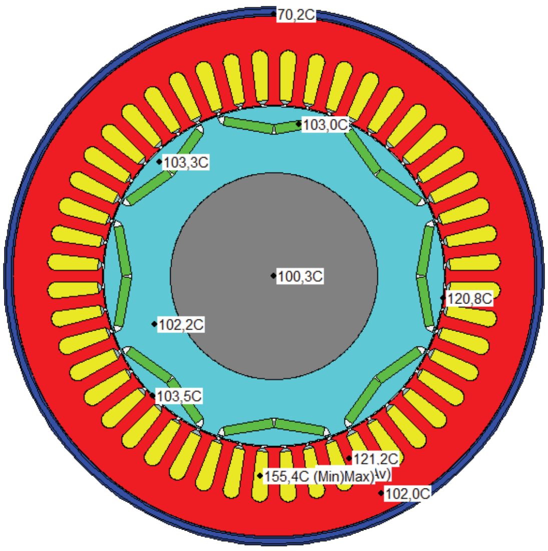

Figure 8: cross section

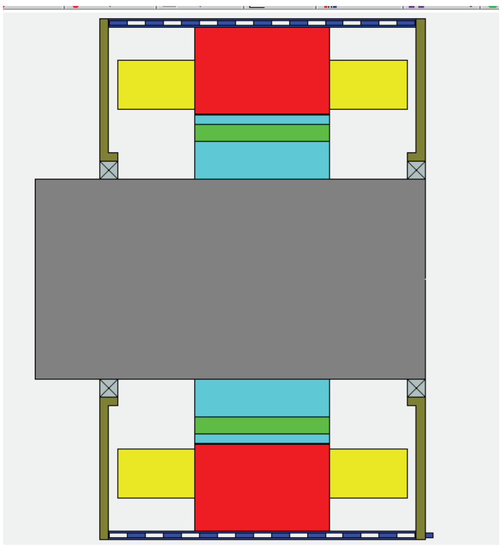

Figure 9: axial section

As regards the winding, you can also specify turns arrangement, as shown on the figure below. The thickness and material of liner, impregnation and insulation can be adapted.

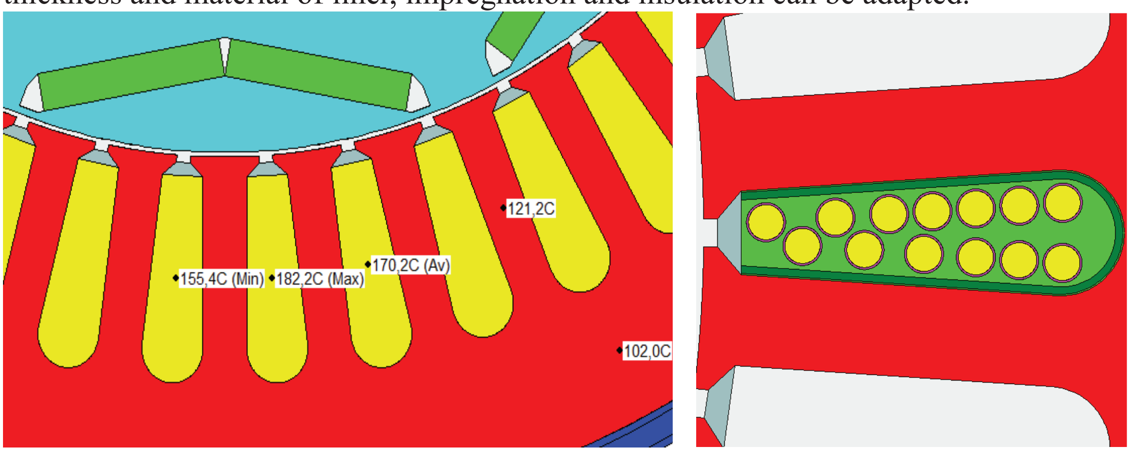

Figure 10: winding definition and temperature

5. Results with Finite Element Analysis

We have selected a working point at 1200 rpm, with maximum current of 100 A. The different losses at room temperature (20°C) and at steady state are summarised in the table below.

	Rotor iron losses	Magnet losses	Coil losses	Stator losses
Room temperature	21.72	2.848	1320	76.53
Steady state temperature	21.152	3.512	2178.9	76.62

Figure 11: Power losses (in W) in different regions versus temperature

For this working point, most losses are coming from Joule losses. The rotor iron losses have decreased with the increase of temperature, which is normal as the remanent flux density has decreased.
And the torque is also impacted, as the remanent flux density is decreased. The average torque is dropping from 226.6 Nm to 218.1 Nm, ie a drop of 4%.

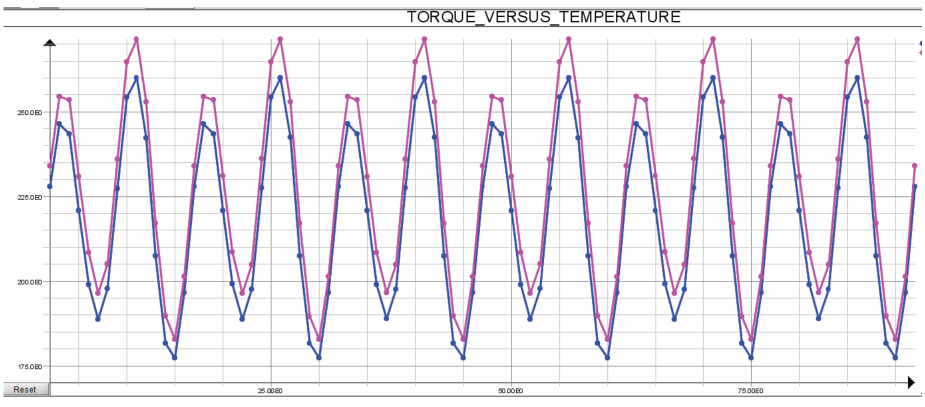

Figure 12: torque versus rotor position for 20°C and for 172.7°C

Now we can display temperature for rotor and stator at steady state.

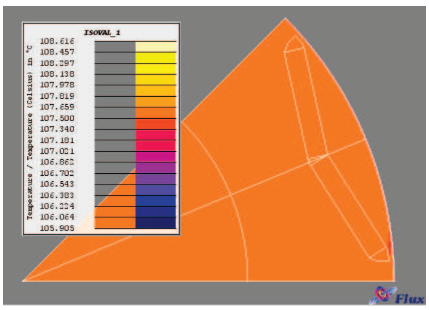

Figure 13: rotor temperature

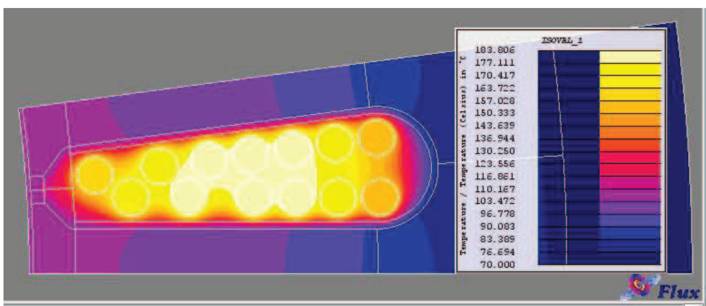

Figure 14: stator temperature

In the rotor, the temperature is quite constant. In the stator, we can see the varying temperature around the different turns oscillating between 140°C and 183°C. We have noted in the next table the temperatures in specific areas in Flux and in MOTOR-CAD.

	Flux (FEM method)	MOTOR-CAD (analytic method)	% of difference
Coil	172.7	170.2	1.5 %
Stator tooth	103.7	121.2	14.4 %
Magnet	106	105.4	0.6 %
shaft	105.8	102.3	3.4 %

Figure 15: comparison between temperatures provided by Flux and MOTOR-CAD

We can observe that temperatures in Flux and in MOTOR-CAD are quite similar for the coil and the rotor. In the stator tooth, there is a difference, probably linked to an interface airgap.
The interest of such a model is that now if we want to take into account of PWM in the current supply, we just need to replace the ideal sine waveform, by the new current waveform. In this case, the iron losses, which are low, may become larger in the stator, which may impact the global thermal behaviour.

Conclusion

Thus, we have proposed a new method for analysing electromagnetic and thermal phenomenon to study the motor behaviour. Electromagnetic computation is carried out over one electric period. Average losses over one electric period are used as inputs for thermal analysis. Transient thermal analysis is split into two different projects: one for stator slot and one for rotor slot. It allows to get a better description of turns disposal. The goal is to decrease as much as possible the size of the finite element models, and to still be able to take into account of important factor for the thermal analysis.
An IPM motor has been studied, focusing on one working point. Steady state temperatures, reached with Flux software and with MOTOR-CAD software are quite close, validating the method.
With Finite Element Method, exchange of data is carried out with command language. The next step of this work may be to make this type of functionality available in a friendlier interface, and to apply it for more complex shape of current.

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