FEM and Lumped Circuit Thermal Analysis of External Rotor Motor

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Abstract – **In the recent years outer rotor motors, mainly brushless ones, have been the object of increasing attention for some specific applications, thanks to their high inertia and other interesting characteristics. However they are particularly difficult to design from the point of view of their thermal behaviour, as the heat is mainly generated form the internal part of the motor and because some mechanical parts involved in the driving system are embedded in the machine and contribute to the heating or cooling of the machine, consequently they cannot be ignored in the thermal analysis. The production of such advanced machines is very demanding of development time and production cost and therefore a fast and reliable thermal design as a preliminary is greatly beneficial.**

I. INTRODUCTION

After the electromagnetic design of an electric machine, often the thermal problem connected with the machine is neglected [1,2]. This is true mainly for two reasons:

- The thermal analysis is particularly difficult to implement in rotating machines as it is strictly a 3D problem, and because the convection factors are not often easy to compute.
- In many cases the overheating of the designed machine is not great and is therefore not seen as a problem. In such cases, a thermal optimization of the machine can be implemented in order to reduce the machine size and production cost.

Often the thermal analysis and eventual optimization are the result of extensive prototype testing. Historically this was the case as software tools suitable for thermal analysis of electric machines were not available or complex to use. Numerical models based on the finite element method (FEM) or computational fluid dynamics (CFD) for thermal and fluid-dynamics calculations, are large and complex when applied to the full 3-dimentional electric machine topology. Putting together a model can take several weeks or months and take hours to solve.

For these reasons, about ten years ago, a specific lumped circuit thermal software, Motor-CAD was implemented by Motor Design Ltd [3], in order to deal with many different kinds of electric motors in different working conditions. One of the latest modules to be written was for external rotor brushless machines: for its special construction a validation was performed in this specific case.

II. LUMPED CIRCUIT ANALYSIS

The external rotor machine was first computed by an electromagnetic simulation software to determine the power losses. The losses were then introduced into the lumped thermal software discriminating the different power sources, which are mainly stator active copper, end winding, back iron, tooth iron, magnet, bearing and windage.

The motor geometry is shown in Fig 1 and 2. The winding configuration is very important for the thermal computation: in this case a multilayer winding was chosen impregnated in a special resin with high thermal conductivity. A representation of the amount of copper and insulation in a slot is shown in Fig 3, the light color representing copper and the dark color insulation.

In the application we are able to use a liquid cooling system to cool the embedded winding in the form of a spiral grove channel system on the inside stator. In the lumped circuit software tool the computation of the heat exchanges with the cooling system takes into account the cooling liquid density, its viscosity and specific heat, as well as the geometry construction. Details of the editor where fluid properties, flow rate and heat transfer coefficient [W/m2/C] is predicted is shown in Fig 4.

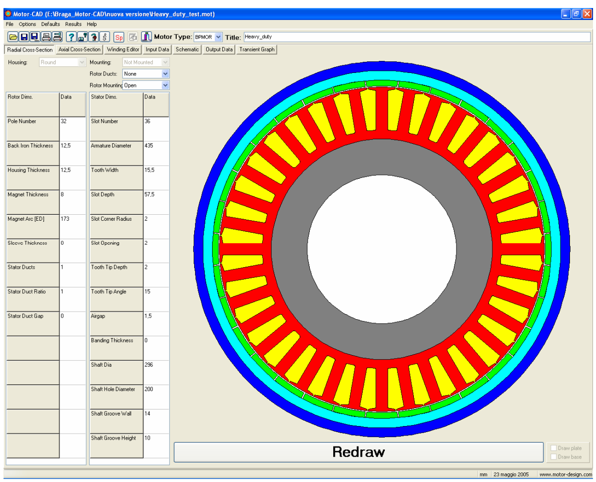

Fig 1: Radial section description of the machine.

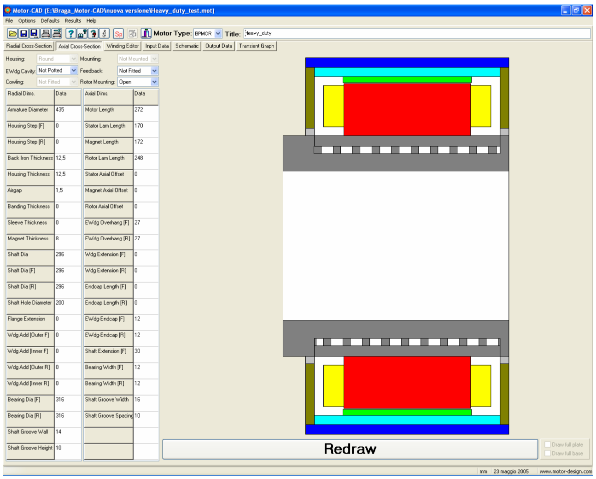

Fig 2: Axial view of the machine

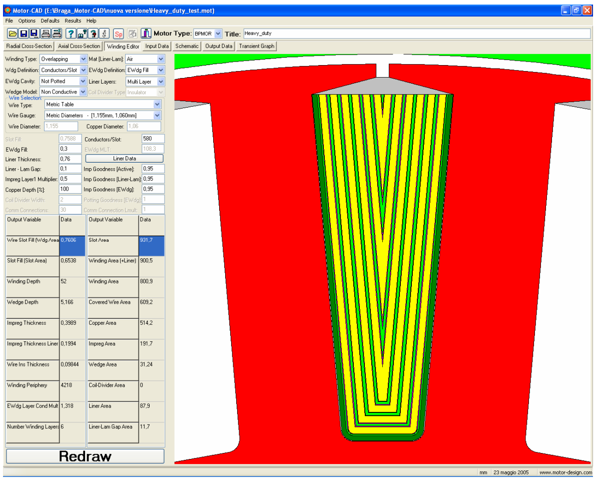

Fig 3: Winding description editor

Fluid Data:

Inlet Temperature:	80	Cp:	1880
Fluid Volume Flow Rate:	6E-6	Kinematic Viscosity:	1.1E-5
Thermal Conductivity:	0.125	Dynamic Viscosity:	0.011
Density:	1000	Pr - Prandtl Number:	165.4

Cooling Options:

☑ Active Cooling Only

Flow Direction:

○ Rear -> Front

◉ Front -> Rear

Component	Input h?	Convection Correlation	h[input] or h[adjust]	Local Velocity Multiplier	Local Fluid Velocity	Re Number	%Re(crit)	h	Notes
Units			W/m2/C	pu	m/s		%	W/m2/C	
Shaft Spiral Groove [Active]	☐	Channel Correlation [Laminar]	1	1	0.0375	41.96	1.824	39.139	

Fig 4: Cooling liquid decription.

The convection heat transfer coefficient due to natural and forced convection effects are automatically computed in the software. The calculation takes full account of such things as the geometry, orientation, air/fluid speed and fluid properties. This is a very important aspect as some geometries within the machine require complex convection calculations consisting of composite convection correlations.

A simple model is used to account for the loss variation with rotational speed. The data and formula used is shown in Fig 5. This is very important if thermal transient calculations involving duty cycle loads with varying speeds are to be modeled.

Loss Variation with Speed:

$$P[speed] = P[input] \times \left[\frac{\text{Shaft Speed}}{\text{Speed[REF]}} \right]^{coef[A]}$$

☑ Speed Dependant Losses

Shaft Speed [rpm]: 165

Component	P[input]	Speed[REF]	coef[A]	W/kg	P[speed]
Units	Watts	rpm		W/kg	Watts
Loss [Stator Copper]	5700	165	0	153.5	5700
Loss [Stator Back Iron]	100	165	0	6.696	100
Loss [Stator Tooth]	100	165	0	2.253	100
Loss [Magnet]	0	165	0	0	0
Loss [Rotor Back Iron]	0	165	0	0	0
Loss [Friction - F Bearing]	2	165	1	0	2
Loss [Friction - R Bearing]	2	165	1	0	2
Loss [Windage]	0	165	0	0	0
Power Injected [Endcap Front]	0	165	0	0	0
Power Injected [Endcap Rear]	0	165	0	0	0
Power Injected [Feet]	0	165	0	0	0
Power Injected [Shaft Active]	0	165	0	0	0
Power Injected [Shaft Front]	0	165	0	0	0
Power Injected [Shaft Rear]	0	165	0	0	0
Power Injected [EWdg Front]	0	165	0	0	0
Power Injected [EWdg Rear]	0	165	0	0	0
Power Injected [Wdg Outer]	0	165	0	0	0
Power Injected [ESpace Front]	0	165	0	0	0
Power Injected [ESpace Rear]	0	165	0	0	0

Fig 5: Input of power losses

The user can easy evaluate the use of different materials in the machine construction. The user can input a components material thermal conductivity, density and specific heat values or select a standard material from the built in material database – Fig 6. The thermal conductivity data is required for the steady state thermal prediction. The other two values are required when a thermal transient calculation is performed. The weight of all components is predicted by the software.

Component	Thermal Conductivity	Specific Heat	Density	Weight Internal Calculation	Weight Multiplier	Weight Addition	Weight Total	Material from Database	Notes
Units	W/m/C	J/kg/C	kg/m3	kg		kg	kg		
Housing [Active]	168	833	2790	0	1	0	0	Aluminium (Alloy 195 Cast)	
Housing [Front]	168	833	2790	0	1	0	0	Aluminium (Alloy 195 Cast)	
Housing [Rear]	168	833	2790	0	1	0	0	Aluminium (Alloy 195 Cast)	
Housing [Total]				0			0		
Endcap [Front]	168	833	2790	1.006	1	0	1.006	Aluminium (Alloy 195 Cast)	
Endcap [Rear]	168	833	2790	0.6058	1	0	0.6058	Aluminium (Alloy 195 Cast)	
Stator Lam (Back Iron)	28	460	7600	14.55	1	0	14.55	Iron (Silicon 2%)	
Stator Lam (Tooth)	28	460	7600	43.24	1	0	43.24	Iron (Silicon 2%)	
Stator Lamination				57.8			57.8		
Copper [Active]	386	400	8954	28.18	1	0	28.18		
Copper [Front End-Wdg]	386	400	8954	4.48	1	0	4.48		
Copper [Rear End-Wdg]	386	400	8954	4.48	1	0	4.48		
Copper [Total]				37.14			37.14		
End Winding Insulation [Fi	0.2	1700	1400	0	1	0	0		
End Winding Insulation [R	0.2	1700	1400	0	1	0	0		
Wire Insulation	0.21	1000	1400	0.9049	1	0	0.9049		
Impreg. [Active]	0.2	1700	1400	1.314	1	0	1.314		
Impreg. [Front End-Wdg.]	0.2	1700	1400	1.548	1	0	1.548		
Impreg. [Rear End-Wdg.]	0.2	1700	1400	1.548	1	0	1.548		
Impreg. [Total]				4.41			4.41		
Slot Liner	0.14	1300	1400	0.02092	1	0	0.02092	Nomex 410	
Ins Slot Base	0.2	1700	1400	0	1	0	0		
Ins Tooth Side	0.2	1700	1400	0	1	0	0		
Magnet	9	420	7400	13.13	1	0	13.13		
Rotor Lam (Back Iron)	28	460	7800	24.67	1	0	24.67		
Shaft [Active]	52	460	7800	51.92	1	0	51.92		

Fig 6: Input of materials properties and weights

The schematic shown in Fig 7 is put together to represent the heat transfer in the machine. This is then solved to calculate the steady state or transient thermal performance. A set of non-linear simultaneous equations are solved for the steady state and an integration technique is used to solve the transient. The temperature at all nodes in the thermal network is calculated together with the power through all the thermal resistances.

For the machine being studied here a high winding temperature was detected, especially in the inner section of the winding. The rotor was relatively cool. However, there was some heating of the magnets by the inner winding.

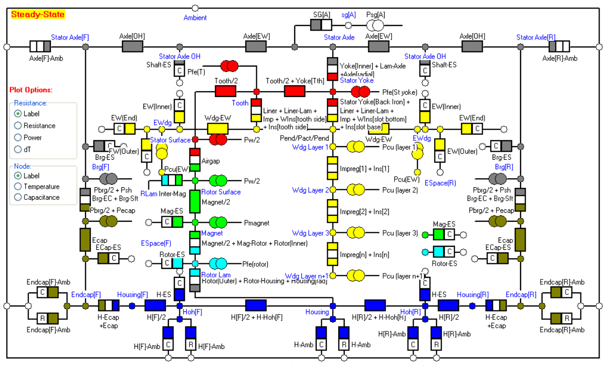

Fig 7: Thermal schematic solved

III. FINITE ELEMENT ANALYSIS

Using the same power losses data, a FEM computation was also performed by means of the thermal module of the finite element software - Flux3D for electromagnetism produced by the company Cedrat [4].

In this case the complete geometry had to be inputted into the simulation tools, describing several details of the machine, as is visible in Fig 8. The 3D description was rather complex, mainly because to take into account the heat transfers, several exchange surfaces were created in the model (for example on the outer surface of the winding and on the outer surfaces of the cooling spiral).

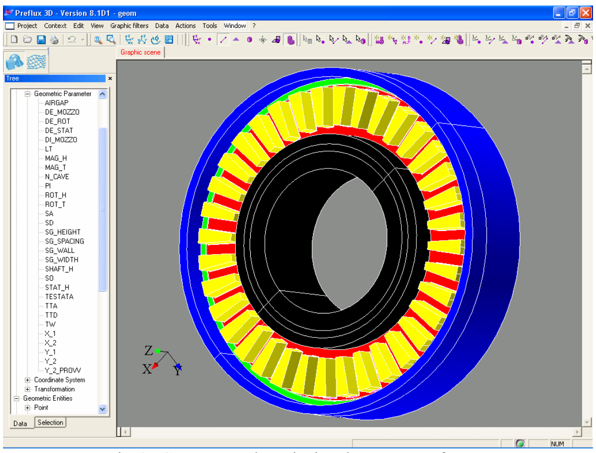

Fig 8: Geometry descritpion by FEM software

The convection exchange coefficients were computed using the Motor-CAD software and introduced into the exchanging surfaces. This is a very important part of the thermal analysis : without the help of Motor CAD a complete CFD computation would have been required.

Some approximation had to be used in the FEM analysis:

- End windings were not modelled as it was not possible to insert a region surface between two conductive region volumes
- Ring shaped Region Volume (green coloured in Fig 8) has been considered instead of modelling 32 separate magnets.
- The winding was described as a single layer.
- Shaft Spiral Groove has been modelled through a series of rings, disposed along the axle of the motor – see Fig 9.
- No windage effects were considered
- No housing was considered

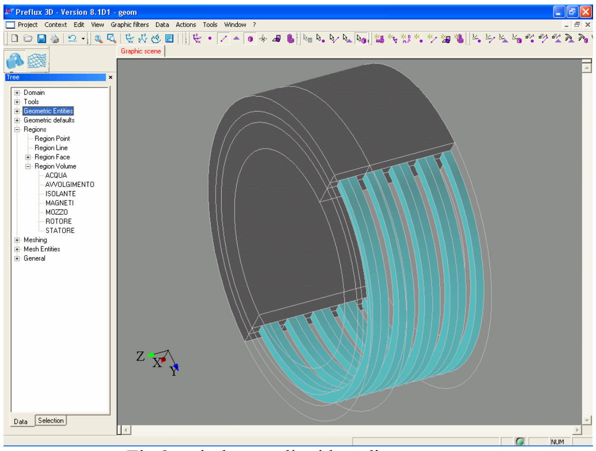

Fig 9: spiral grove liquid cooling system.

As can be seen form the previous list, the 3D FEM model, even if rather complex, is just a simplification of the complete thermal model. Nonetheless the most important parts involved in the thermal behaviour of the machine, that is the winding plus its liner, stator and rotor lamination, spiral liquid cooling system and aluminium separators, were considered in the FEM computation. Typical FEM results are shown in Fig 10.

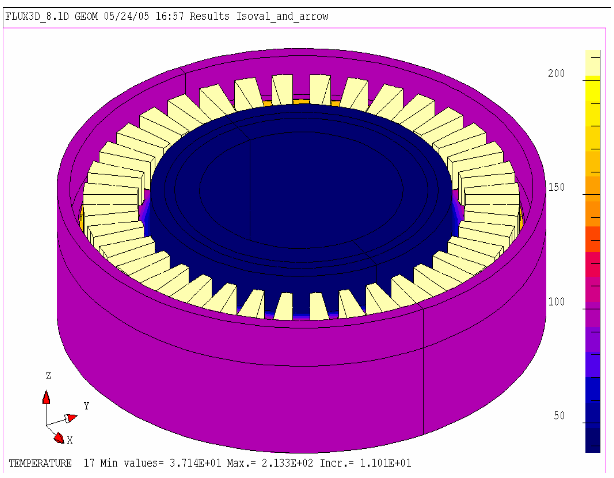

Fig 10: FEM computation of temperature distribution.

IV. COMMENTS ON LUMPED CIRCUIT AND FEM RESULTS

1. The considered comparison parameters have been the temperature in the stator winding, as this was preliminarily considered the most delicate value for the integrity of the machine. While Motor-CAD can distinguish between different winding layers, in the FEM software an average value of the winding over temperature has been computed, as a consequence of geometry simplification. Motor-CAD predicts the winding temperature to be in the range 223 to 242 °C. The average winding temperature in the Flux model is 215 °C. The computed difference is between 4% and 13 %.

2. The good agreement can partly be related to the fact that the convection coefficient computed in Motor-CAD is used in the Flux model. Moreover, we can also state, after the FEM validation, that the complex machine construction was correctly computed by the lumped circuit simulator.

3. The time aspect is also very important: they are completely different for the models obtained by the lumped circuit software and with the FEM method. For the lumped circuit software the computation time is about 1e3 times less than for the FEM. Also in the case of the construction time the differences are very relevant: with Motor-CAD the model can be input in about a hour, allowing several different sensitivity analysis and optimization steps. While the FEM model requires a complex CAD input and a very specific knowledge of the software, even if introducing some simplifications.

For this reason the lumped circuit software can be considered a valid tool for the thermal design and optimization of motors.

We can also mention the practical consideration as a consequence of this analysis; before constructing a prototype some modifications were suggested, mainly affecting the magnet choice and the cooling system design. These factors can produce a saving in the high cost of machine assembly.

IV. ACKNOWLEDGMENT

The author thanks the company Spin Applicazioni Magnetiche Srl for the design data

V. REFERENCES

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