Finite Element Modelling of Thermal Contact Resistances and Insulation Layers in Electrical Machines

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Abstract: Small transition layers with a significant temperature drop, such as thermal contact resistances and thin insulation layers, are difficult to represent in thermal finite element models of electrical machines. A new approach using mesh cuts and duplicated nodes at the thin layer position is derived and discussed. Practical examples demonstrate the features of the methods used.

Keywords: thermal modelling, finite element methods, eddy currents, electro-thermal effects

I. INTRODUCTION

To accurately determine of the control parameters for electrical machines such as induction motors, it is important to know the temperature distribution inside the device. In particular, the temperature of the windings of induction machines influences the time constants of the machine and hence the behaviour of field controlled drives. In permanent magnet machines the torque production capability depends on the temperature of the magnets [1]. The accurate knowledge of the temperature allows protection against insulation damage and magnet demagnetisation.

Thermal modelling of electrical machines is often performed using of lumped parameter networks allowing to include thermal resistance due to contact transitions and thin insulation layers at several places of the electrical machine. Thermal modelling using the finite element method (FEM) allows more detailed models, especially when coupled to electromagnetic FEM-models with an accurate loss calculation.

II. THERMAL CONTACT RESISTANCES IN ELECTRICAL MACHINES

Thermal contact resistances can be found at several locations inside electrical machines.

- Contact frame/stator yoke: The stator iron and the frame are held together under a certain mechanical pressure. Due to the rough surface of the stacked yoke, small air pockets exist between both parts. Hence the contact conditions vary locally [2]. External conditions such as ambient and operating temperature influence the contact conditions.
- Contact (stator) winding/slot: Between the bare conductor strand and the stator iron, several layers of insulation are found. It is common practice to replace the single conductors and individual conductor insulation by an equivalent material [3]. However, the slot insulation and the related contact resistance have to be modelled separately.
- Contact rotor bar/slot: If the rotor winding consists of bars, contact resistance is depending on the way of construction (e.g. injection moulding or bars).
- Contact rotor yoke/shaft: In machines with a significant heat production in the rotor (e.g. induction machines), the heat path through the shaft has to be modelled. A thermal contact resistance exists between rotor and shaft.
- Glue layer between a permanent magnet and the yoke: In a permanent magnet machine, a small thermal barrier exists between the ferromagnetic iron and the magnet. This is important if the effect of losses in the magnets is studied, as required for NdFeB magnets due to their temperature dependent characteristics.

To quantify the thermal contact resistance, a coefficient h_c is defined [4]. The thermal conductance of the insulation layers has to be known. The temperature dependency of these parameters causes the thermal model to become non-linear.

III. FEM MODELLING OF THIN LAYER THERMAL BOUNDARIES

To model thin layer thermal boundaries, different approaches can be applied.

A. Non-scaled finite elements

Finite elements with the exact dimensions of the layer are troublesome if the size of the overall FEM-model is large compared to the layer. Due to round-off errors, the nodal coordinates tend to become almost identical, leading to badly conditioned elements. In order to obtain an acceptable aspect ratio of the for example triangular discretisation, a huge amount of elements has to be used to model the contact layer and adjacent regions. The high number of slots in a typical electrical machine and the small size of the contact layer in one direction causes a significant growth of the model size and hence the computation time.

An advantage is however that an identical – but large – thermal FEM discretisation can be used as basis for the electromagnetic FEM-model used to determine the joule or iron losses in the elements.

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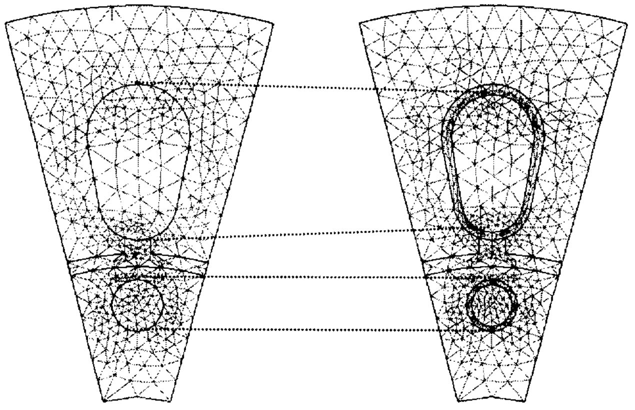
B. Scaled finite elements

The before mentioned numerical problem can be solved by introducing an element layer, with larger scaled dimensions [5]. Similarly, the thermal conductivities of the contact layer and the conductor part have to be scaled as well, leading to an equivalent anisotropic material. This is a more interesting alternative to non-scaled elements. A problem arises when the heat sources have to be imposed on every element. If the same scaled mesh would be used to calculate the losses, a substantial error in the electromagnetic field solution may arise. The enlarged contact layer would have to be modelled as non-ferromagnetic, leading to an incorrect leakage flux.

If a different electromagnetic mesh is used, a non-trivial non-isomorphic projection is applied to avoid an erroneous heat source distribution (fig. 2).



(a) electromagnetic mesh (b) thermal mesh

Fig. 2. Non-isomorphic projection of electromagnetic loss solution on the thermal mesh.

C. Modelling using a single equivalent material

The idea of this approach is to apply a correction to the thermal conductive properties of the bulk material, usually a conductivity in order to obtain the correct temperature at the surface of the layer. This causes an error in the internal temperature distribution of the conducting region, but the average temperature is computed accurately. Despite the averaging error, this approach has the advantage of a clear geometrical relation between the elements of the regions in the different sub-problems. This is advantageous for projection methods.

Figure 2 shows the lines of constant temperature of an induction machine with the thermal conductivities of the stator and rotor winding adapted [6].

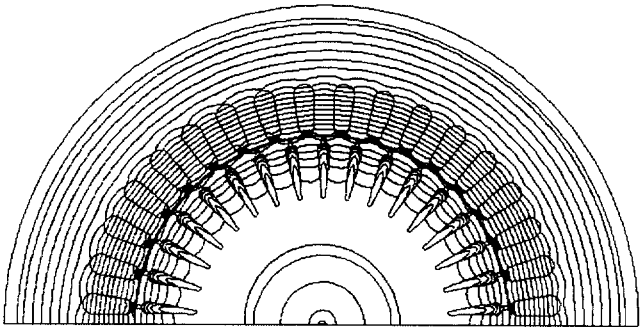


Fig. 2. Thermal model of an induction machine using equivalent thermal conductivities for the conductors.

D. Mesh cuts and duplicate nodes

A new approach with an obvious geometrical relationship between the thermal mesh and the mesh for the electromagnetic field problem to compute the losses is proposed. Moreover no averaging errors are made and the material properties need not to be altered.

Double nodes are put at the edges marking the position of the thermal barrier (Fig. 3). These extra degrees of freedom in the FEM model are linked by extra terms in the set of equations describing the thermal relationship of the mathematically adjacent nodes. Such nodes are geometrically laying on top of each other.

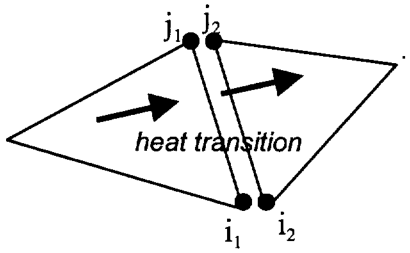


Fig. 3. Adjacent elements with a duplicated common edge on the location of the thermal barrier.

The standard meshing algorithms need to be adapted to generate the extra nodes in a consistent way without crossing element edges.

Standard element matrices are generated. The extra matrix for first order triangular elements (1) is added to the system. The exact values of the coefficients are obtained using a Galerkin approach based derivation. Extensions for higher order and hierarchical elements are possible. The right-hand side of the system remains unchanged.

$$\begin{array}{c|ccccc|} & i_1 & j_1 & \cdots & i_2 & j_2 \\ \hline i_1 & \frac{h_c l_e}{3} & \frac{h_c l_e}{6} & \cdots & -\frac{h_c l_e}{3} & -\frac{h_c l_e}{6} \\ j_1 & \frac{h_c l_e}{6} & \frac{h_c l_e}{3} & & -\frac{h_c l_e}{6} & -\frac{h_c l_e}{3} \\ \vdots & \vdots & & \ddots & & \vdots \\ i_2 & -\frac{h_c l_e}{3} & -\frac{h_c l_e}{6} & & \frac{h_c l_e}{3} & \frac{h_c l_e}{6} \\ j_2 & -\frac{h_c l_e}{6} & -\frac{h_c l_e}{3} & \cdots & \frac{h_c l_e}{6} & \frac{h_c l_e}{3} \end{array} \quad (1)$$

with:

h_c : contact resistance coefficient
l_e : length of adjacent element edges

A simplified thermal model of an induction machine is shown in fig. 4. It contains a stator slot and a rotor bar. The thermal contacts between the windings and the iron are built in the described way, leading to a set of isothermal lines appearing to be discontinuous. This is not true since many isothermal lines are situated at the apparently discontinuous temperature jump in the thermal contact layer.

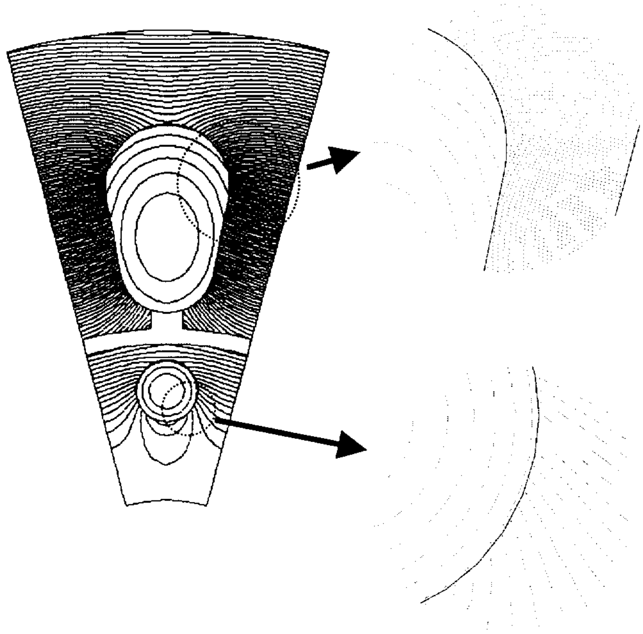


Fig. 4. Example obtained using the novel approach to model the thermal barriers around the conductors.

An advantage of this method is the clear relationship between the electromagnetic loss-calculation mesh and the thermal mesh.

A minor disadvantage is the extra computation time in the mesh generation, being relatively unimportant when compared to the overall solution time. There is also a slightly increased number of off-diagonal non-zeros in the system matrix.

CONCLUSION

The importance of the accurate modelling of thin thermal barriers such as contact resistances and insulation layers present in different parts in electrical machines, is outlined. Four different approaches used to model these layers in thermal FEM-models coupled to FEM-based electromagnetic loss models are discussed. Among them, a new and advantageous approach is derived and applied using duplicated nodes and cut meshes on the location of the thin thermal barrier.

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