Coupled Magneto-Thermal Simulation of Thermally Anisotropic Electrical Machines

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Abstract: Algorithms allowing to obtain the steady state coupled thermo-magnetic fields of electrical machines such as induction machines, permanent magnet synchronous machines with surface magnets or dc-motors are proposed. These machines are thermally anisotropic since they show radial heat flow paths with different thermal conductivities while rotating. The novel method is based on an iteration loop involving a single magnetic finite element (FEM) model and one or two thermal FEM models.

Keywords: thermal modelling, finite element methods, eddy currents, electro-thermal effects, permanent magnets, induction machines, synchronous machines

I. INTRODUCTION

The performance of electrical machines depends on the temperature distribution inside the machine.

- Changes in the electrical conductivity lead to a different slip in induction machines and the joule loss distribution alters as well. The rotor resistance influences the time constants of the machine, requiring robust control schemes.
- The characteristics of rare earth permanent magnets vary with elevated operating temperature, leading to a lower performance at higher temperatures. The magnets have to be protected against demagnetisation due to high temperatures.
- The lifetime of a machine firmly depends on hot spots in the insulation.

Therefore, coupled thermo-magnetic modelling in the design stage of the machine is recommended. Mostly, the finite element method is used to compute the field variables, allowing to obtain a detailed field distribution within an acceptable computation time.

II. COUPLED FIELD MODELLING OF ELECTRICAL MACHINES

A. Magnetic/thermal field simulation

The magnetic field is described by the magnetic vector potential, calculated using a standard triangular finite element mesh [1]. Usually a 2D modelling, extended with circuit equations is sufficient to compute joule and iron losses in cylindrical electrical machines. The electromagnetic torque value can be obtained from this field solution.

The thermal field is computed by a finite element simulation [2] as well.

B. Coupled iteration

The material properties used to assemble the magnetic equation system are temperature dependent. This causes the coupled field problem to be non-linear. Different algorithms exist to solve the coupled problem. A first possibility is based on the consecutive solution of the single field types until convergence is reached. Another possible method is the composition of fully coupled equation system in which the solutions of both fields are calculated simultaneously. Both methods suffer from specific numerical problems [3]

III. MODELLING OF THERMALLY ANISOTROPIC ELECTRICAL MACHINES

A. Induction machines

The heat flow through induction machines without forced cooling or surface mounted cooling fins is usually directed radially inside the machine. The preferred heat flow path thereby leads through opposing teeth and in a worst case the path leads through opposing slots. In [4] it is proposed to calculate both of these extreme positions in a slice model and average both situations to obtain a mean temperature. Here, it is proposed to calculate the temperature distribution of an induction machine using a model with the minimal symmetry properties: for the 4 pole machine of figure 1, having stator slots and rotor slots, half of the machine has to be meshed.

Depending on symmetry, many geometrical slot-tooth combinations can be considered in such a model, each having a specific preferred heat flow path. While rotating, every tooth and slot encounter each of these relative positions many times. The heat source values in the machine depend on rotor position and time (indicated by arrows in fig. 1: showing where the values of the losses are found at different instances of time when this mesh is used for a magnetic calculation). Based on a single steady state magnetic field simulation with appropriate heat sources post-processing, a local average of the loss can be obtained by a radial averaging procedure. This can be understood as an examination of the time dependency of the losses, which is transformed into a position dependency. These loss values serve as input for the thermal model used to obtain the averaged temperatures for updating the magnetic model. The mean steady-state temperature can be approximated by a similar radial averaging over related positions in the teeth and slots of the temperature distribution. This second averaging is necessary to cancel out the effect of the position dependent heat flow paths.

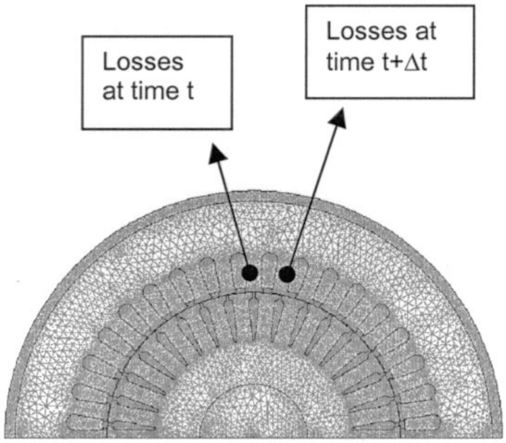


Fig. 1. Mesh used to build the thermal finite element model of an induction machine

The chart in figure 2 summarises all operations. Averaging is performed by rotating the solution over an appropriate angle related to stator and rotor symmetry, followed by a projection and addition of the scaled field solution.

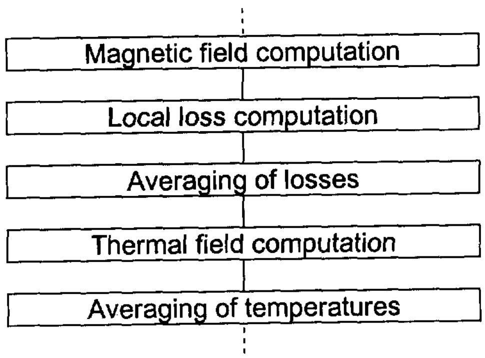


Fig. 2. Flow chart for the thermal modelling of induction machines.

An entire transient solution recommends large computation time, and leads to more accurate results. The proposed method is a faster alternative representing a compromise between computational expenses and accuracy.

B. Permanent magnet machines

Generally, in permanent magnet (PM) machines such as dc-motors and synchronous machines with surface-mounted magnets and/or rotor anisotropy, the mentioned approach must be varied. In the induction machine the slot/tooth period is small enough to allow spatial averaging as an approximation for time averaging. In PM-machines, the number of poles determines the spatial period. However, a fast thermal modelling technique is still possible by means of calculations with two related thermal models.

From the stator viewpoint (static frame), the fast revolving rotor can be modelled as a rotating cylinder with a set of heat source densities, which are only a function of the distance to the centre of the machine ('shell model'; fig. 3a). These axisymmetric values (e.g. magnet or armature joule losses) are obtained by spatial smoothing of the post-processing results of the magnetic problem. This model leads to the recommended temperature information to update the stator material data.

A second model is referred to the rotor (Fig. 3b). Now, the heat sources in the stator are smoothed. The radial heat path is changing periodically as seen from the revolving rotor. Therefore, to obtain a locally constant heat flow density from the rotor surface, which is close to reality due to the high rotational speed, an equivalent axisymmetric averaged material can be assumed, filling the equivalent stator 'shells'. From this model, the rotor temperatures are extracted.

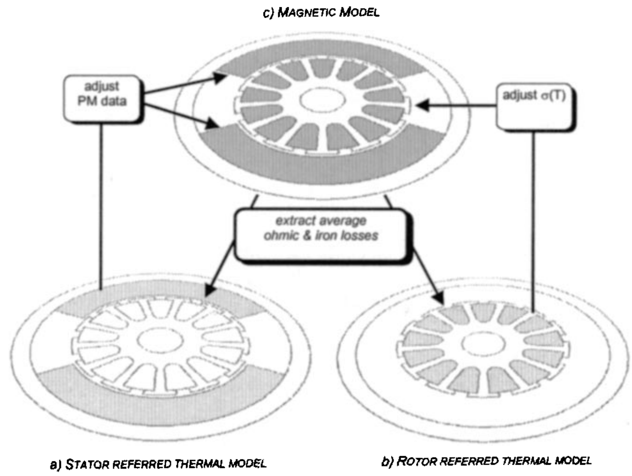
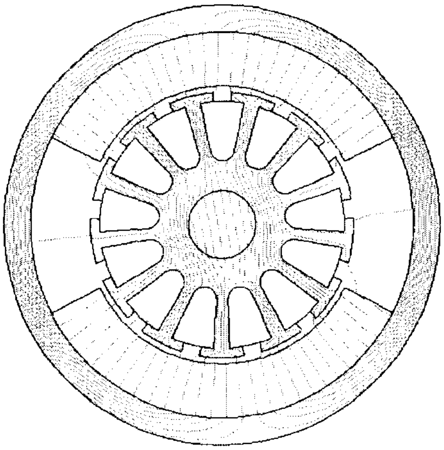


Fig. 3. Three model algorithm for PM machines.

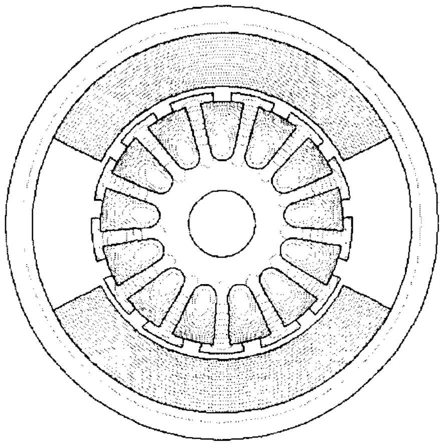
The tools such as the averaging operation, necessary to perform the calculation schemes are implemented in the in-house finite element package 'Olympos'.

An application is shown in figure 4. A small permanent magnet dc machine designed to operate in variable ambient conditions is modelled using the "three model algorithm". The machine is voltage driven, so the temperature rise decreases the current; the field of the magnets is weakened by the higher internal temperature. Details about the design can be found in [5].

If the "three model algorithm" would not have been used, and the thermal calculation were conducted with only one static thermal model, the erroneous thermal image of fig. 5 would be the result clearly showing no symmetry in the thermal gradient within the slots.



(a)



(b)

Fig. 4. (a) Magnetic flux lines of a loaded dc machines in operation; (b) composed image of averaged thermal field lines.

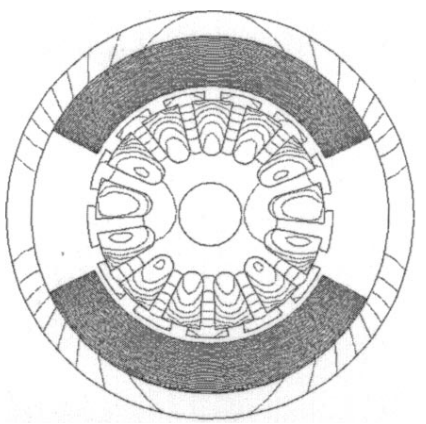


Fig. 5. Erroneous thermal image obtained if the "three model algorithm" is not used for this type of machine.

CONCLUSION

Algorithms to perform coupled thermo-electromagnetic finite element calculations using a single magnetic and one or two thermal models are proposed. Time dependent losses in induction machines are translated to position dependent values evaluated from the single finite element solution and transferred to a thermal finite element model. The thermal anisotropy of the opposing slot/tooth combinations is handled by radial averaging of the temperature. The thermal anisotropy in permanent magnet machines can be tackled by using a "three model algorithm" in the reference frame of the stator and of the rotor combined with partial representation of the relatively rotating part by 'shell models'. Practical applications are presented.

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