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Coupled physics solvers for analysing the magneto-thermal behaviour of a permanent magnet synchronous machines

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The aim of this study is to present a thermal analysis of a permanent magnet synchronous machine based on the finite element method. The developed model can be used to predict temperature distribution inside the studied motor during the rated operation. Electromagnetic computation (EM) is carried out with the aid of two 2D finite-element (FE) simulations on the cross-section of the PM motor. To analyse the process of heat transfer (HT) in an electrical machine, empirical correlations are used to describe the convective (HT) from the different surfaces of the PM motor. The (HT) coefficient is determined using dimensionless numbers. The proposed numerical method to solve the coupled problem is based on independently and successively solving the (EM) and thermal problems and then transferring the results between the two sub-problems. The results obtained by the model are compared with experimental results from testing the prototype electric motor.

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1 Abridged version of the paper

The main objective of our task is to develop a finite element model to analyze the thermal effects in electric machines during its various operating conditions. In electrical machines, the permanent magnets and the insulation in the stator windings are sensitive to temperature variations, so special attention must be paid to this part because the high temperature can affect the durability of the stator winding insulation and the efficiency of the permanent magnets. The prediction of the temperature distribution inside an electric motor is required at the machine design stage in order to control the temperature rise and to avoid overheating of the sensitive parts. The accuracy of the thermal model depends on the material properties and the knowledge of losses in the electrical machine. This leads to a formulation that couples the heat transfer and Maxwell equations. The mathematical model is formed by the transient (HT) equation together with the electromagnetic power losses generated inside the PM motor and the electromagnetic equation (EM) with temperature dependent material parameters.

In section 2, we first recall the heat transfer problem (1) and some assumptions are presented in order to simplify the thermal model. The windings and the stator are treated as a homogeneous medium with equivalent thermal parameters and the effective properties to characterize the thermal behavior are calculated based on the volume-weighted average overall constituents. For heat transfer through the external surface of the machine, we consider natural convection. On the other hand, the internal air gap is defined as solid and the effective conductivity to characterize the thermal behavior of the air gap is calculated from empirical correlations, and this hypothesis allows us to avoid the very time-consuming CFD simulations.

$$\text{3D Thermal equation (HT):} \quad \rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (-\lambda \nabla T) = Q(T), \quad (1)$$

where ρ represents the density, λ is the thermal conductivity and Q is the heat source. According to the developed method, a transient 3D FE thermal were carried out using the open-source library Feel++ [4]. The main reasons for choosing Feel++ software are that its toolboxes provide the tools that (i) give users the ability to parameterize the model properties, (ii) offer solving strategies to be run in multiprocessor or multi-core environments and (iii) save at every step the simulation results which can be further processed in tools like Paraview.

In section 3, the electromagnetic field computation is based on the time-stepping finite element method for the permanent magnet (PM) motor. The electric machine can be analysed as a two-dimensional problem if we assume that the physical behaviour of the machine is the same in axial direction. The two-dimensional magnetic field formulation of calculation is based on magneto-dynamic Maxwell's equations, which leads the following partial differential equation [1].

$$\text{2D Magnetic equation (EM):} \quad \nabla \times \left(\frac{1}{\mu(H)} \nabla \times A \right) = J_s - \sigma(T) \frac{\partial A}{\partial t} + \nabla \times H_c, \quad (2)$$

where A is the z -component of the magnetic vector potential, $\mu(H)$ the magnetic permeability which is dependent on the magnetic field intensity and $\sigma(T)$ is the electrical conductivity. The source terms, J_s and H_c are the z -component of the source current density and the coercive field strength of the permanent magnet. The electromagnetic computation is carried

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out with the aid of two 2D finite-element (FE) simulations on the cross-section of the PM motor. In the developed FEM model, total losses including winding loss and iron loss are simulated in Maxwell, ANSYS software. The core loss of electric machine with sinusoidal excitation is commonly computed based on loss separation, which breaks the total core loss into static hysteresis loss, classic eddy-current loss and excess loss components [1–3]

$$p_{\text{core}}(t) = p_{\text{hyst}}(t) + p_{\text{ec}}(t) + p_{\text{exc}} = \left\{ \left| H \cdot \frac{dB}{dt} \right|^{\frac{2}{\beta}} \right\} + \left\{ \frac{1}{2\pi^2} k_{\text{ec}} \cdot \left(\frac{dB}{dt} \right)^2 \right\} + \left\{ \frac{1}{C_c} k_{\text{exc}} \cdot \left(\frac{dB}{dt} \right)^{1.5} \right\} \quad (3)$$

where $p_{\text{hyst}}(t)$, $p_{\text{ec}}(t)$ and $p_{\text{exc}}(t)$ are the static hysteresis loss, the classical eddy current loss and the excess loss, respectively. The parameters k_{ec} , k_{exc} and coefficients β , C_c required for the calculation were determined based on the core manufacturer-provided loss curves [3].

In section 4, the equations (1) and (2) are coupled because the temperature resulting from the thermal computation is used for evaluation of the material characteristics in the magnetic equations and the power losses resulting from the magnetic computation are used as heat sources in the thermal model. The proposed numerical method to solve the coupled problem is based on independently and successively solving each sub-problem and then transferring the results between the two sets of the equations. The coupling is realized weakly due to the different time scales for (HT) and Maxwell equations. Since the thermal phenomena is slowly varying in comparison with electromagnetic field, the coupled problem is discretized in time with a time step reflecting the thermal scale to avoid unreasonable computational times.

Let us consider that the simulation time period is split into time intervals: $t_{\text{initial}} = t_0 < t_1 < \dots < t_n < \dots < t_N = t_{\text{stop}}$, t_n is the time where the data is exchanged between the two sub-problems. The size of each interval is determined based upon the variation of material properties in the electromagnetic problem. Hereafter, we assume that the temperature variations are not significant, meaning that the electromagnetic properties remain approximately the same in each sub-interval. The main interest of such a decomposition is that the (HT) problem can be solved several times over the sub-interval $[t_n, t_{n+1}]$. The algorithm for the time period between t_n and t_{n+1} , is composed of 2 steps:

1. The iteration process starts from an (EM) simulation and the recalculation of the electromagnetic losses. The average of all temperatures calculated over the previous time period is used to determine the electrical conductivity in (EM) problem.
2. The losses are then fed into the thermal simulation and the (HT) problem continues to be solved without correcting the heat sources during certain times until the variation of the electrical conductivity not exceed certain limit. As soon as the electrical conductivity variation becomes significant, the calculated temperatures are fed back to the (EM) simulation for another time period.

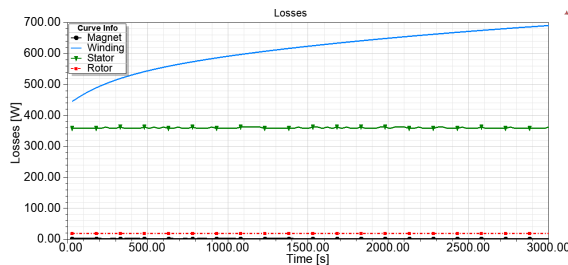


Fig. 1: Electromagnetic losses calculated during the simulation.

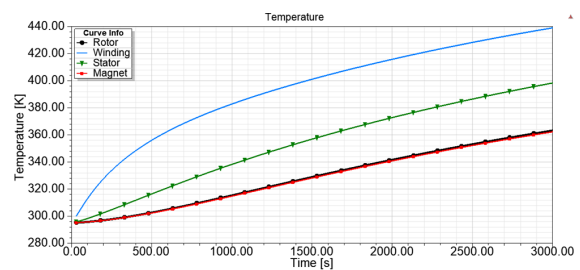


Fig. 2: Temperature calculated during the simulation.

In the section 5, the proposed thermal model is implemented using the open source Feel++ software [4] and two examples are presented to assess the accuracy of the developed coupled solvers. In the first example, the numerical results are compared with the experimental ones, which are obtained from a prototype machine and the simulated temperatures distribution are very accurate for critical parts of the electric machine such as winding, rotor and magnets. Fig. 1. and Fig. 2. show the electromagnetic losses and the temperature variations in different parts of motor obtained in the second example. In the last section we present the conclusions of this research and perspectives for future works.

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