

Transient Coupled Magnetic Thermal Analysis of a Permanent Magnet Synchronous Electrical Vehicle Motor

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ABSTRACT

The transient coupled computation of the magnetic and thermal field of a permanent magnet excited synchronous motor for a vehicle application is discussed. The coupling of the magnetic and dual thermal models is accomplished through a detailed loss calculation and the temperature dependence of the permanent magnets and conductive materials. Both fields are calculated by means of the FEM method on independent meshes. In order to avoid numerical problems, the field and loss calculations are performed on different time scales. The simulation methods are applied to a six-pole 45 kW PMSM machine for different working conditions. The results are compared with measurements.

Keywords: permanent magnet synchronous machines, coupled thermal-magnetic problems, FEM

1 INTRODUCTION

The thermal-magnetic behaviour of electrical machines and of permanent magnet synchronous machines in particular, is important for various reasons:

- *Lifetime prospective:* Local overtemperatures damage the winding insulation. When the permanent magnets are too hot, irreversible demagnetisation may occur, changing the operational characteristic. The prediction of these effects may be used to extend the machine's lifetime.
- *Robustness of drive systems:* Machine parameters required for drive control, such as the induced voltage and resistances occurring in time constants, change with the internal temperature. A more detailed knowledge of the parameter evolution helps in the design of a robust drive control.

To study the internal temperature evolution, a coupled thermal magnetic simulation tool is indispensable. The magnetic and electrical material parameters change locally with the temperature distribution. The heat sources are mostly of electromagnetic nature: joule and iron loss. Hence, a two-way interaction between the magnetic and thermal field exists. The methodology outlined here, uses FEM models along with FEM based loss calculation algorithms. Combinations with 2D as well as 3D models are used.

Here, it is chosen to use independent meshes for the subproblems. This allows to obtain meshes that are adaptively optimised using specific subproblem error estimators. Additionally, it becomes possible to allow a more efficient inclusion of subproblem specific items, such as thermal contact resistances, having no importance for the magnetic field. The penalty for this is the use of field projections, but by implementing efficient search algorithms, this represents a limited computational cost.

The calculation methodology is applied to a six-pole electrical vehicle motor, a 45 kW permanent magnet synchronous motor, designed for dynamic operation. The time evolution of this device under different working conditions is simulated and compared to prototype measurements.

2 TRANSIENT COUPLED SIMULATION METHOD

2.1 Time scale problem

Several time constants and scales are important in the coupled model. At first, the small time scale in which the revolution and the fundamental magnetic field changes take places. Local field changes, important for the loss calculation occur on an even smaller scale. On the other hand, the thermal phenomena have very large time constants.

The combination of the time scales with a high ratio in time constants yields a very stiff transient problem. An exact transient solution requires that the time-step is at least smaller than the smallest time constant. This is computationally expensive when a large time span (the heating-up time) has to be simulated. Hence, the magnetic model with the small time constants is preferably transformed into a model suitable for simulation on the larger time scale.

2.2 Magnetic field model

The 2D magnetic field equation is written in terms of the magnetic vector potential [1]:

$$\nabla \cdot (\nu(A(t)) \nabla(A(t))) = -\sigma(T(t)) \left(V_s(t) + \frac{dA(t)}{dt} \right) - \nabla M(T(t)) \quad (1)$$

with: A : z-component of the vector potential
 T : Temperature

ν : Reluctivity
 σ : Electrical conductivity
 V_s : Source voltage
 M : Permanent magnet source field

q : Total losses
 k : Thermal conductivity
 ρ : Mass density
 c : Specific heat

The induced voltage term is developed as:

$$\sigma(t) \frac{dA}{dt} = \sigma(t) \left(\frac{\partial A}{\partial t} + \vec{v} \cdot \nabla A \right) \quad (2)$$

For a rotating PMSM, the effect of the second term in (2) containing the speed \vec{v} , representing the voltage induced by the rotation, is dominant over the local field changes described by the first term. However, these changes contribute to the losses (e.g. in the magnets). The first term in (2) is neglected in the global field calculation, the second term is calculated separately, by extracting the fundamental induced voltage [2]. It is then substituted in (1) as a finite difference (3). The parameter θ originates from the time stepping method [1].

$$\begin{aligned} \sigma(t) \frac{dA}{dt} &\approx \sigma(t) (\vec{v}(t) \cdot \nabla A) \\ &\approx \theta \sigma(t_{n+1}) \vec{v}(t_{n+1}) \cdot \nabla A(t_{n+1}) + (1 - \theta) \sigma(t_n) \vec{v}(t_n) \cdot \nabla A(t_n) \end{aligned} \quad (3)$$

Consequently, the magnetic model is reduced to a series of (semi-)static magnetic field computations with externally determined currents, computed once per thermal time-step. The temperature dependent material properties change with the pace of the thermal model's time-step.

2.2 Dual thermal field models

To calculate the thermal field evolution, two models are required to overcome the time scale problem [3]:

1. a thermal model in the reference frame of the stator, allowing to determine the temperature of the stator windings; the rotor is seen as a cylinder body with equivalent materials. This model is used to update the electrical conductivities in the winding.
2. a thermal model in the reference frame of the rotor, allowing to determine the temperature of the rotor windings; the stator is seen as a cylinder body with equivalent materials. This model is used to update the permanent magnet data.

The use of these different models (and meshes) overcomes the problem of the changes at the time scale of the rotation, such as position dependent heat flow paths (constantly changing slot and tooth positions) and loss density changes becoming time dependent due to the rotation.

To use these models, which can be calculated in parallel, efficient projection and averaging operations for the solution and the losses are required. The thermal field equation is:

$$\nabla \cdot (k \nabla(T)) - \rho c \frac{\partial T}{\partial t} = -q(A, T) \quad (4)$$

with: T : Temperature

To model stator water cooling, causing heat flows in the radial direction, these models are extended with convection boundary conditions. In cases where the heat flows have a more 3D character, e.g. an external natural air cooling, 3D models can be used, and/or thermal circuit extensions can be made [4].

The air gap is represented by means of an equivalent heat-conducting material. The equivalent conductivity is calculated considering the thermal resistance obtained by considering two convective transfers in series. The convective heat coefficients are calculated considering the state of the air flow in the air gap [5]. Convection parameters for the inner parts are difficult to determine. Mostly, similar cases published in literature are used to estimate the values.

Equivalent anisotropic materials or special element relations are used to model thermal contact resistances and thin insulation layers [6].

2.3 Loss calculations

The following losses are taken into account and are determined based on the FEM solution(s):

- *Stator winding Joule losses*: This loss density is computed by calculating the joule loss integral in every winding finite element. Eddy current contributions are not present in general due to the small size of the strands.
- *Iron losses*: These have different components (hysteresis, eddy current and excess losses) and are calculated by numerically integrating, for every finite element, analytical expressions using the field changes during one rotation [7]. These values are calculated based on the flux loci in the elements, obtained from the set of semi-static magnetic models, each rotated over a small angle. Hence, rotational effects are counted in.
- *Permanent magnet Joule losses*: These occur in electrically conductive surface mounted permanent magnet blocks and are calculated under the simplifying assumption that they do not affect the global magnetic field, so the first term in (2) can be reconstructed in the permanent magnet finite elements based on the set of semi-static magnetic models [8]. This approach takes into account the higher field harmonics.

To calculate the iron losses and joule losses in the elements, a set of finite element magnetic field solutions, at consecutive rotation angles is required. The same solution set is used for both. These FEM calculations are performed relatively fast, since the saturation can be 'frozen' yielding a linear problem. Fig. 1 visualises the obtained flux loci in a tooth.

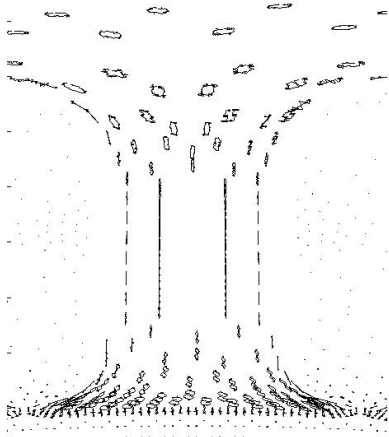


Fig. 1. Reconstructed trajectories (loci) of the endpoints of the magnetic field vector in different locations in a tooth of the PMSM at partial load.

2.4 Coupled computation

For every time step, the coupled solution is determined iteratively. First, the magnetic field is solved, followed by the loss calculation procedure and the torque angle estimation. Consequently, the new thermal solutions are determined after which the material parameters are adjusted. It is tried to keep the time steps sufficiently small in order to limit the iterations to one or two loops. The previous time step solutions then function as an excellent initial solution for the non-linear computation.

3 PMSM MODEL CALCULATIONS

To study the dynamic performance of a 45 kW six-pole PMSM designed for use in an electrical vehicle [2], a transient coupled thermal magnetic simulation is performed. This machine is designed to have a water cooling system and contains conductive, temperature sensitive NdFeB permanent magnet pieces fixed to the rotor surface.

For the simulations and tests, the device is set-up as a generator, driven at a constant speed. No-load tests as well as tests with a resistive load are performed. As the losses in the no-load case were very low, this test is performed with an inactive water cooling; then the device is cooled by natural air convection of the frame.

3.1 Magnetic FEM model

Due to the symmetry, only one pole pitch is modelled. For the magnetic field and related loss calculation, 2D models are used. Fig. 2 shows two meshes used for the loss calculation procedure. As different meshes are used for every rotation angle, the field has to be partially rotated back and projected on the reference mesh elements, for which the losses are estimated.

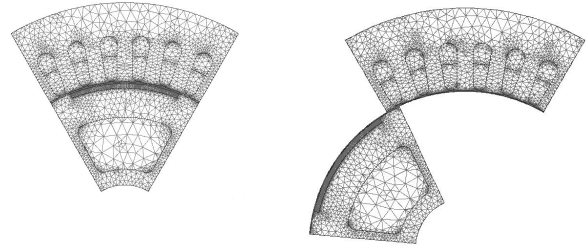


Fig. 2. Two meshes used in the procedure to calculate the iron and permanent magnet eddy current losses.

The electrical conductivity and, where applicable, permanent magnet data, are thermally adjusted in every finite element. Such characteristics are assumed to be constant within one element. It is chosen to use sufficiently small first order finite elements as a compromise to model as accurate as possible the material data changes due to the coupling. The torque angle, calculated along with the induced voltage [2], is adjusted in every (thermal) time step. Fig. 3 shows the field solution in the obtained steady-state in the load test.

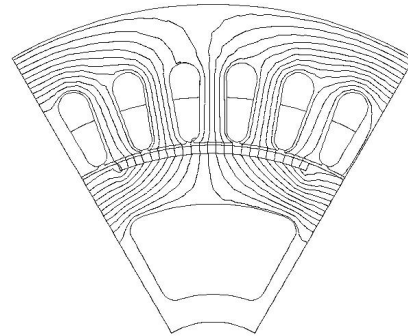


Fig. 3. Magnetic field solution of the PMSM in loaded conditions.

3.2 Thermal FEM models

The choice concerning the use of a 2D or 3D approach for the thermal mesh is made based on the advantages and drawbacks of both. A 2D model implicitly assumes a planar heat flow, whereas a 3D model allows more complicated paths, especially when the frame is fully modelled. The best results were obtained by using 2D models for the situation with active water cooling: due to the very strong cooling mechanism, the heat flow is almost entirely radially oriented; the frame influence appears neglectable. The 3D approach (Fig. 4) is used for the situation relying on natural convection.

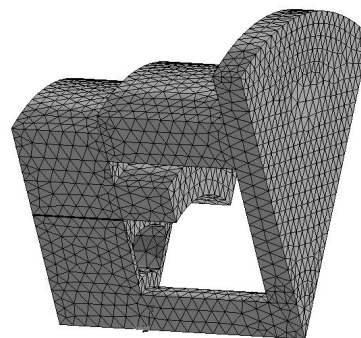


Fig. 4. 3D thermal model (rotor frame) of the PMSM.

When 3D thermal models are used along with 2D magnetic models, adapted projection methods are required.

A particular problem is the determination of the internal air temperature in this model. This temperature is assumed to be constant, as the air is mixed constantly. Its value is estimated by a weighted average (5) of the surface temperatures of all the element faces involved. The weights are calculated from the surfaces S_i and local convection coefficients h_i . This weighted average can be understood as the temperature on a node in circuit model connecting convection resistances to this node.

$$T_{air,int} = \frac{\sum_i S_i h_i \bar{T}_i}{\sum_i S_i h_i} \quad (5)$$

The determination of the internal convection parameters (as well as the thermal contact coefficients) is not obvious. To initially estimate them, similar situations published in literature were used [9].

Fig. 5 and Fig. 6 show steady-state thermal solution in the loaded situation, obtained using the 2D models. Only the field lines in the relevant parts are drawn.

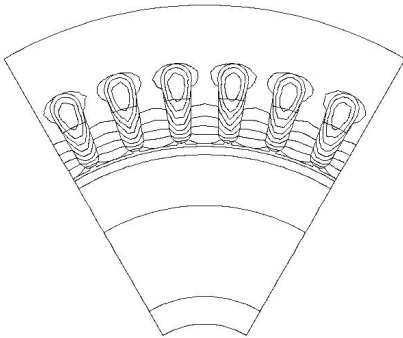


Fig. 5. PMSM thermal solution - stator frame model; used to update the winding electrical conductivity.

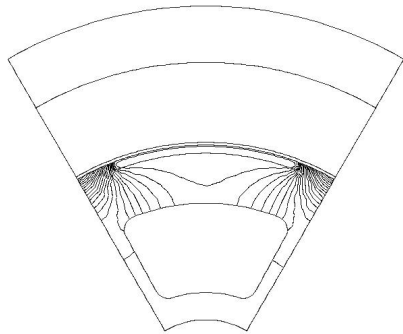


Fig. 6. PMSM thermal solution - rotor frame model; used to update the permanent magnet data.

3.3 Comparison with measurements and discussion

In a first test, the machine is used as generator driven by a DC motor at 1500 rpm. Its Y-connected winding is linked to a resistive load of 6.4 kW. The water cooling is active. All types of losses are considered in the motor. The iron losses in the stator amount about 10^5 W/m^3 , with a maximum of $3 \cdot 10^5 \text{ W/m}^3$ at the tooth surface. These values drop about

20 % when the iron gets hot and the permanent magnet induced flux is weakened. The joule losses in the winding are about $1.6 \cdot 10^5 \text{ W/m}^3$ for this load, rising about 19 % due the heating. The eddy current loss in the magnet pieces is estimated as $8 \cdot 10^3 \text{ W/m}^3$.

Temperatures registered by the sensors are compared to computed values (Fig. 7). The 2D thermal models already lead to satisfying results; 3D models are not required. This is explained by the dominant water cooling, removing the heat very efficiently: the radial heat flow is very dominant. Neglecting the air convection mechanisms at the outside and in the end-winding region does not significantly change the result. The measured points are the average of the redundant sensors. An interval is marked around them, indicating the variance (about $\pm 3^\circ$) of the measured values.

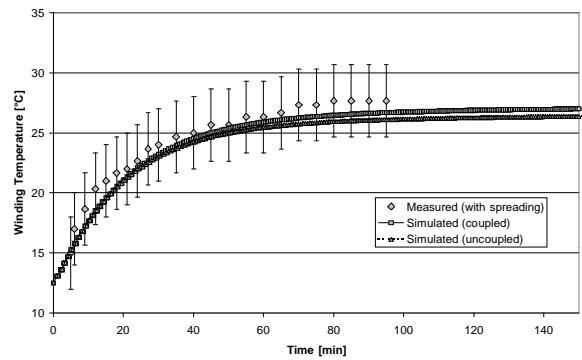


Fig. 7. Comparison of measured and calculated winding temperature variations in water-cooled loaded conditions (the variance coming from redundant sensors is indicated).

In this graph, a good agreement between measured and simulated data is found. The results of an uncoupled calculation are plotted as well, these are situated below the coupled result, since the increased resistivity is not taken into account, introducing a systematic underestimation of the losses. The variance between the coupled and uncoupled simulation is not large, it represents a difference of about 4.4 % for this limited temperature rise of merely 15°C .

In the no-load test, the PMSM is driven by the DC motor at 3000 rpm. The windings are open and the induced voltage is measured. The water cooling is inactive. In this case, the iron losses have a range of $3 \cdot 10^5 \text{ W/m}^3$. The losses in the magnets amount $3.6 \cdot 10^5 \text{ W/m}^3$. The evolution of the registered temperatures, along with the simulations is shown in Fig. 8. The variation of the fundamental measured and induced voltage is given in Fig. 9.

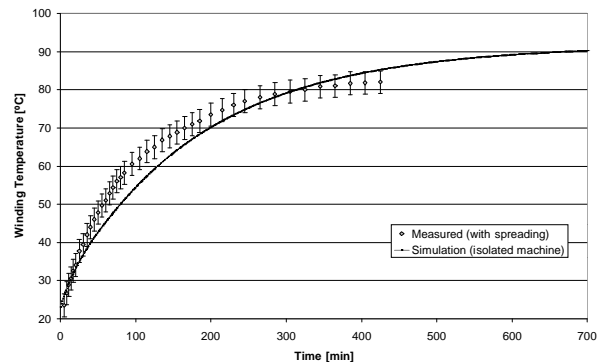


Fig. 8. Comparison between simulated and measured temperatures in air-cooled unloaded conditions (the variance in the measured values is indicated).

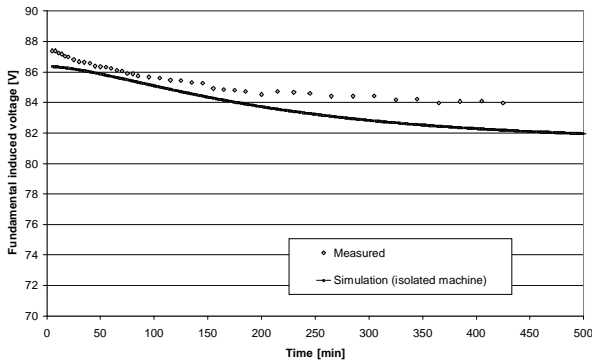


Fig. 9. Comparison of fundamental measured and induced voltage.

The first graph indicates that the computed steady-state temperature of the device is about 5 % higher than measured. An explanation is found in the fact that some parasitic heat paths are neglected. Neither the heat flux through the mounting (the motor is not perfectly insulated from the base plate on the test bench), nor the heat flowing out of the motor through the rotating shaft is taken into account. A test calculation, in which limited heat fluxes are added, indicates that the temperature drops to the measured level, when it is assumed that these conductive phenomena add an extra heat path, increasing the cooling capability by 10 %.

For the measurements, the stator temperature rises a bit faster in the beginning. This is due to the convection cooling models used, becoming more accurate when the temperature differences are more significant. There is also an uncertainty regarding the quantity of the remaining water in the cooling channels.

The induced voltage follows the measured value, which is an indirect measure of the magnet temperature. In the temperature range occurring in the simulation, an average change of more than 5 % of the magnets' remanent field is found. After a while, the simulations indicate a higher temperature and a lower voltage drop than measured. This can be explained considering the shaft, heating up indirectly and exporting some heat from the rotating motor parts, yielding a cooler rotor at steady-state in reality. The modelling uncertainty regarding the true fluid flows contributes to the registered differences as well.

4 CONCLUSIONS

An approach to perform transient coupled electromagnetic-thermal computations using FEM models is presented and applied on a PMSM model. Special attention is paid to the time-scales of the problems involved. A 2D semi-static magnetic FEM problem and two thermal 2D or 3D FEM problems are to be solved in a coupled way for every time-step. Loss calculation procedures allowing to estimate the effect of field harmonics in iron and eddy current losses are outlined.

Computations compared to tests on a prototype illustrate the results that can be achieved by adopting a coupled modelling approach.

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