An extended dynamic thermal model of a permanent-magnet excited synchronous motor

Christelle Piantsop Mbo'o and Kay Hameyer

RWTH Aachen University, Institute of Electrical Machines
Schinkelstr. 4, 52056 Aachen, Germany, e-mail: christelle.piantsop@iem.rwth-aachen.de

Abstract **- This paper presents a dynamic thermal model of a PMSM to estimate the temperature at specific points of the machine during operation. The model is implemented using thermal network theory, whose parameters are determined by means of analytical approaches. Usually thermal models are initialised and referenced to the room temperature. However, this can lead to incorrect results, if the simulations are performed when the electrical machine operates under "warm" conditions. An approach is developed and discussed in this paper, which captures the model in critical states. The model gives feedback by online measured quantities to estimate the initial temperature.**

I. THERMAL NETWORK MODEL

Thermal monitoring of electrical machines is required to highly utilize the electrical machine in every point of operation. A suitable thermal model allow a fully use of the thermal capacity of the machine. The temperature of the permanent-magnet excited synchronous motors (PMSM) with buried rotor permanent-magnets and equipped with a concentric winding in star-connected is modeled using a seven node thermal network (Fig. 1) [1]. The network consists of heat sources (P), thermal resistances (R_{thi}) and capacitances (C_{thi}). Each element of the electrical machine, which is a heat source, is represented as a temperature node. The temperature nodes are: the housing (θ_1), the stator yoke (θ_2), the stator tooth (θ_3), the slot windings (θ_4), the end windings (θ_5), the permanent-magnets (θ_6) and the bearings (θ_7).

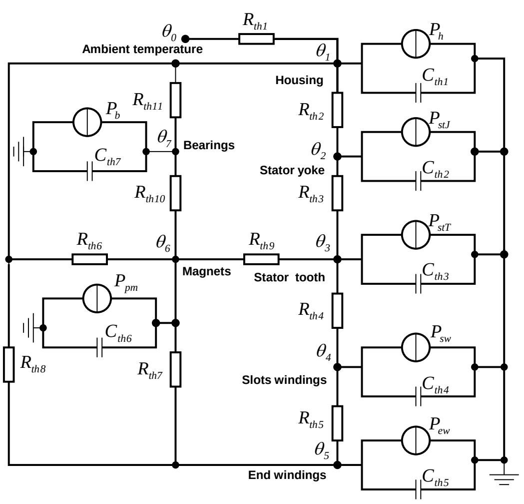

Fig.1. Thermal network model.

The rotor is modeled by a parameter (magnet), which corresponds to the average rotor surface temperature. The thermal resistance between the ambient temperature and the housing R_{th1}, the housing and the stator tooth R_{th2}, the stator tooth and the stator yoke R_{th3}, the stator yoke and the slot windings R_{th4}, the slot windings and the end windings R_{th5}, the stator yoke and the magnet $R_{th9,}$ the magnet and the bearings R_{th10}, the bearing and the housing $R_{th11,}$ depends on the thermal conductivity of the materials λ and the thickness of the layer t between the two solids. There is a heat transfer by convection from the internal air to the housing, the end-windings and the magnets. The thermal resistance of the internal air is enclosed to the thermal resistance $R_{th6,}$ $R_{th7,}$ R_{th8}. These resistances depend on the convective heat transfer coefficient, which is calculated using the expressions given by [1]. The analytical approach used to determine the resistances is given by [1], [2] and [3]. The thermal resistances R_{th1} and R_{th4} have a great influence on the estimated temperature. These values may not exactly be determined using the analytical approach because of probable manufacturing tolerances and an unusual stator shape of the motor. For this purpose, the resistances are determined by measurements at stand still of the machine and blocked rotor. The machine's winding is supplied by the nominal direct current and heated up to the thermal steady-state.
The thermal network in Figure 1 shows the thermal capacitance, which is required to simulate the transient-state temperature distribution in the motor. Its value depends on the mass m_i and the specific heat capacity c_{pi} of the parts of the machine. It is calculated by (1), where i represents a node:

$$C_{thi} = m_i \cdot c_{pi} \tag{1}$$

II. DYNAMIC THERMAL MODEL

In order to estimate the temperature of each part of the machine, the machine losses have to be determined. Here, the losses consist of the ohmic losses, the iron losses and the friction losses. The ohmic losses due to the stator currents in the slots P_{sw} and in the end windings P_{ew} are determined according to the variation of temperature of the slot θ_4 and end-winding θ_4.

$$P_{sw,ew} = 3 \cdot R(\theta_{4,5}) \cdot I^2 \tag{2}$$

The iron losses consist of the hysteresis losses P_h, the eddy-current losses P_{ec} and the excess losses P_{ex}. These are computed using a transient 2D-FE approach and a post processing formula defined in [4]. According to which the eddy-current losses and the excess losses are computed from the contribution of each harmonic of the flux density over one electrical period in time. The hysteresis losses are computed as a function of the peak value of the magnetic flux density over the same period. These losses are calculated for some value of the current and the frequency and added to evaluate the total iron loss for the corresponding working point of the machine.

$$P_{fe} = P_h + P_{ex} + P_{ec} \quad (3)$$

The eddy-current density of the magnets is integrated over the magnet volume and multiplied by its specific conductivity to determine the eddy-current losses inside the magnets. The eddy-current density is calculated by means of a transient 3D-FE approach. Figure 2 shows the iron loss of the stator and the eddy current loss of the permanent magnet related to the current and the speed of the machine.

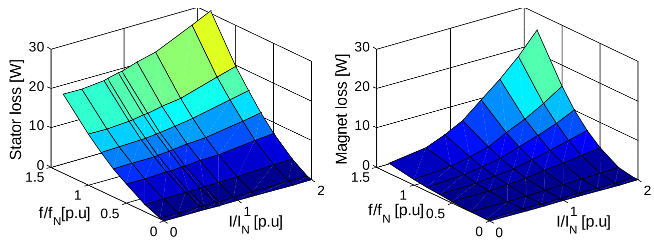

Fig.2. Iron loss of the stator and magnet loss.

After the computation of the losses, the thermal resistances, and capacitances, the temperature of each node is computed by solving the differential equation given as:

$$C_{thi} \cdot \frac{d\theta_i}{dt} = \frac{1}{R_{th,ji}} \cdot (\theta_j - \theta_i) + P_i \quad (4)$$

The indexes i and j represent two different nodes. The differential equations of all nodes constitute a system of equations. The system is presented in the state space form and is implemented in Matlab/Simulink to estimate the node's temperatures.

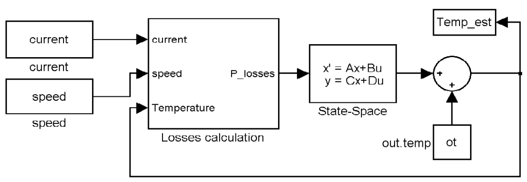

Fig.3. The dynamic thermal model.

The model shown in Figure 3 consists of a subsystem for the losses estimation, in which the iron losses and the magnet losses are integrated in the form of a look-up-table. The ohmic losses are calculated from a closed-loop using the winding temperature. The model's input parameters are the actual current, the speed and the ambient air temperature (*ot*).

III. MODEL EVALUATION

The test motor is a permanent magnet synchronous motor with star-connected concentric winding. The star connector is not available. To evaluate the model, five temperature sensors are placed at the end-windings (drive-side and shaft-end), in the slots windings (top and bottom) and at the housing of the tests motors. The motor with a locked rotor is fed by the nominal direct current and heated up to thermal steady-state. This measurement is used to determine the thermal resistance R_{th1} and R_{th4}. The simulated temperature rise in comparison to the measured one is plotted in Figure 4. The mean value of the end-windings temperature and the slot windings temperature is compared to the simulated data. The Table I shows the temperaure at the steady state .

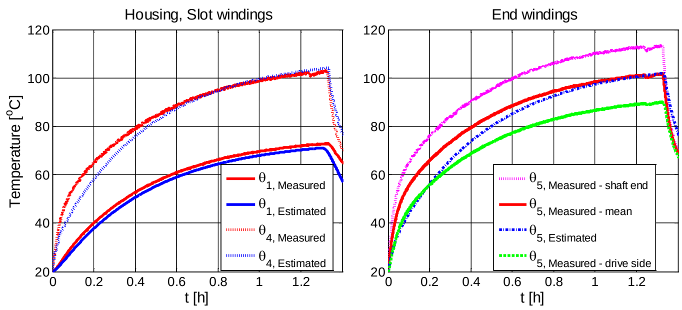

Fig.4. Temperature rise by locked rotor operation.

TABLE I
COMPARISON OF THE RESULT AT THE STEADY-STATE

Temperature nodes	**Measured**	**Simulated**
Housing θ_1	*72.82°C*	*71.06°C*
Slot winding θ_4	*102.93°C*	*104.16°C*
End windings θ_5	*101.77°C*	*101.92°C*

This model shows a maximum deviation of *3%* in comparison to the measured data. The second focus is to implement a method to generate the initial temperature of the machines parts at critical states for example, after a new start of the system, when the motor is heated up.

IV. CONCLUSIONS

This contribution presents a thermal network model for a permanent magnet synchronous motor. The main part of the paper discusses the computation of the thermal resistances, capacitances and heat losses. A dynamic thermal model and its first results are presented. The next step is to evaluate the model at different working points and to implement the method to capture critical state. This will be discussed in the full paper.

REFERENCES

[1] J. Lindström, “Thermal Model of a Permanent-Magnet Motor for a Hybrid Electric Vehicle”, *Department of Electric Power Engineering, Chalmers University of Technology Göteborg*, Sweden, 1999.

[2] G. Kylander, “Thermal modelling of small cage induction motors, PhD. Dissertation, *School of Electrical and Computer Engineering, Chalmers University of Technology Göteborg*, Sweden, Tech. Report. 265, 1995.

[3] G. D. Demetriades, H. Z. de la Parra, E. Andersson, and H.Olsson, “A real-time thermal model of a permanent-magnet synchronous Motor”, *IEEE Transactions on Power Electronics*, vol. 25,No. 2, pp. 463-474, 2010.

[4] G. Bertotti, A. Boglietti, M. Chiampi, D. Chiarabaglio, F. Fiorillo and M Lazzari, “An improved estimation of iron losses in rotating electrical machines”, *IEEE Trans. Magn.*, vol. 27, No. 6, pp. 5007–5009, 1991.