MULTIPHYSICAL SIMULATION IMPROVES ENGINEERING OF ELECTRIC DRIVES

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Abstract

In many electric drive applications – especially road and rail vehicles – dimensions and weight of the electric machine are crucial factors. Taking the time varying load conditions of such drives into account, fast and accurate prediction of the machine's electro-mechanic and thermal behavior over a given load cycle is essential to achieve a design that is neither too small nor too large; these results are desired in an early phase of the drive's engineering process. Additionally the cooling method is limited by the application's specification, influencing the thermal behavior respectively the utilization of the machine's active part. To support the design engineer, both an electro-mechanical model – taking all loss sources into account – and a thermal model – considering the cooling method – have been developed. For this challenging multiphysical modeling task, the object oriented modeling language Modelica is used. The main focus of the presented models is extensibility, easy adaption for different cooling methods, satisfying accuracy and performance of the simulation. To validate the developed models, simulation results are compared with measurements of a 4-pole standard induction motor 400 V / 50 Hz, 18.5 kW, totally enclosed fan cooled (TEFC). The drive is tested under varying load conditions, monitoring electrical, mechanical and thermal quantities.

Keywords: Multiphysical modeling and simulation, electric drives, Modelica.

Presenting Author's biography

Anton Haumer was born in 1957 in Vienna. He received the Dipl.-Ing. (M.Sc) degree in electrical engineering from Vienna University of Technology, Austria, in 1981. He worked for 15 years at ELIN Union AG, later VA Tech ELIN EBG, in various positions in the field of electric drives, especially development and design of electric motors. 1997 he achieved the license "Technical Consulting - Electrical Engineering". After some more years of experience in the field of electric measurement, sensors and automation, as well as power supply systems he began to work as a self-employed technical consultant. Since 2004 he is associated with Austrian Institute of Technology, Vienna, Austria. His main interests are development and simulation of electric drives. As a member of the Modelica Association, he developed several Modelica Libraries for the simulation of electric drives and acted as the Program Chair of the 5th International Modelica Conference 2006.

1 Introduction

The design process of an electric machine normally starts with the electro-magnetic design according to the requirements of the specific application, using either conventional design software or finite element methods. The appropriate sizing of the active part also depends on the cooling method and the load cycle. If the machine has to be designed for operation under constant conditions, especially constant load S1, examination of the prospective temperature rise can be done by using conventional programs (e.g. [5]) as well as finite element software. The results of such an investigation will show the thermal utilization of the machine: If the crucial temperatures (especially winding temperatures) do not meet the expectations respectively the requirements, either the active part has to be redesigned or the cooling method has to be adapted. However, if the machine is specified to operate under varying load conditions, the specific load cycle has to be taken into account. This can only be done by means of dynamic thermal simulation. Considering different cooling arrangements, it is advantageous to design thermal models in a modular object-oriented way.

A more detailed investigation shows that the operating temperatures influence the electrical parameters of points of operations, too: The winding resistances are temperature dependent, thus influencing parameters like slip and efficiency. Furthermore, the dissipated losses depend on the temperature dependent resistances, which influence the temperature rise. To take these effects into account, an electro-magnetic model has to be coupled with a thermal model of the machine. In many cases, this can result in stiff DAEs (differential algebraic equation systems), since electro-magnetic time constants normally are much smaller compared with thermal time constants. To solve such stiff problems, either appropriate solver algorithms have to be chosen or co-simulation methods have to be considered.

Since the same active part can be combined with different cooling concepts, as well as the same cooling concept can be used for different active parts, even different machine types as asynchronous induction machines or permanent magnet synchronous machines, a modular design of such models is desired. For the presented work, Modelica has been chosen: Modelica is an object-oriented equation-based language to conveniently model complex physical systems containing, e.g., mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented subcomponents, which can be described by means of (also nonlinear) algebraic and ordinary differential equations (with respect to time). Essential for object-orientation is the connector concept, where pairs of quantities (potential and flow variables) are used to describe interaction between components.

2 Drive model

2.1 Electro-mechanical model

As described in [2], the behavior of three-phase induction machines is modeled by means of space phasors ([3]). For the instantaneous phase voltages v_1, v_2, v_3, the space phasor and the zero sequence component of voltage are:

$$\underline{v} = \frac{2}{3}\left(v_1 + v_2 e^{+j2\pi/3} + v_3 e^{-j2\pi/3}\right) \qquad (1)$$

$$v_0 = \frac{1}{3}\left(v_1 + v_2 + v_3\right) \qquad (2)$$

From equations (1) and (2), we determine the back-transformation:

$$v_1 = v_0 + \mathrm{Re}\left(\underline{v}\right) \qquad (3)$$

$$v_2 = v_0 + \mathrm{Re}\left(\underline{v} \cdot e^{-j2\pi/3}\right) \qquad (4)$$

$$v_3 = v_0 + \mathrm{Re}\left(\underline{v} \cdot e^{+j2\pi/3}\right) \qquad (5)$$

Applying space phasor therory implies that only the base harmonic of the spatial magnetic field distribution in the airgap is taken into account, which is sufficient for many investigations.

The machine models are equipped with two three-phase electric connectors (beginning and end of the three stator windings), a mechanical connector (shaft), an optional mechanical connector (housing) and a thermal port, as shown in Fig. 1.

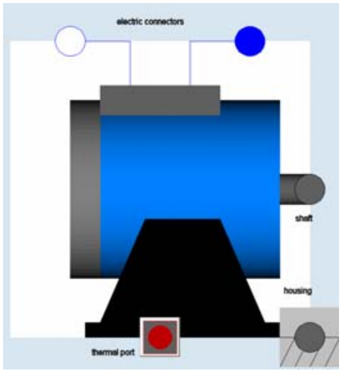

Fig. 1 Electro-mechanical model of an asynchronous induction machine

All loss models dissipate their losses either to an internal thermal ambient, or to the external thermal port, as shown in Fig. 2. This way a proper power balance is guaranteed whether the external thermal port is used or not.

Using this thermal port, the actual losses determined in the electro-mechanical model can be fed to a thermal model of the investigated machine. Furthermore, the actual temperatures – determined by the thermal model – are reported back to the electro-mechanical model, influencing the point of operation.

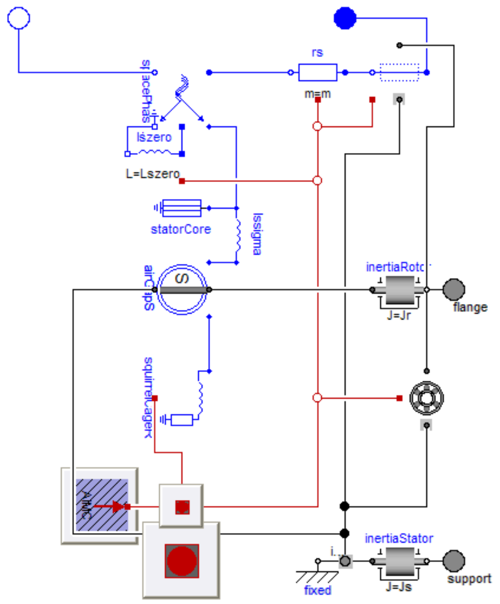

Fig. 2 Object-oriented structure of the machine model

The losses are modeled as described in [7]:

- Temperature dependent copper losses
- Core losses
- Friction losses
- Stray load losses
- Brush losses (where applicable)

2.2 Thermal model

The thermal model is designed as a thermal equivalent circuit (8). The components of such a thermal network are:

- Nodes being regions of constant temperature.
- Injecting the losses to the thermal network.
- Thermal capacitors representing the ability of storing heat energy in a certain region.
- Thermal resistors representing heat conduction between nodes of solid regions.
- Thermal conductors with non-constant thermal conductance representing heat transfer from solid to coolant fluid, taking flow velocity into account.

Additionally, components representing coolant flows are needed. The following quantities are chosen to describe the state of a coolant flow:

- Pressure and temperature as potentials
- Mass flow and energy flow (associated with mass flow, taking medium properties into account) as flow variables.

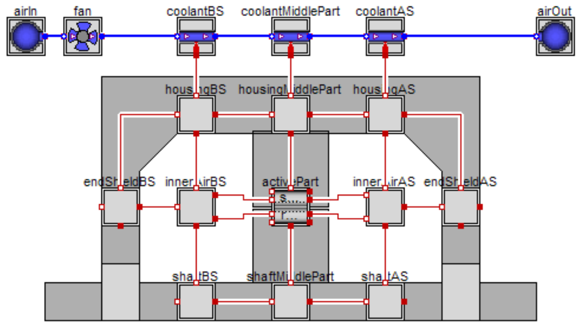

Fig. 3 Thermal model of an asynchronous induction machine

According to [5], heat transport associated with a coolant flow, cannot be described by heat conduction equations, but the energy balance of the medium has to be taken into account.

3 Comparison of simulation and measurement

3.1 Device under test

The models have been verified by comparing simulation results with measurements. The device under test was a standard 4-pole asynchronous induction machine with squirrel cage, totally enclosed fan cooled (see Fig. 3 and Fig. 4), designed for operation at 400 V Δ / 50 Hz. The parameters of the machine are summarized in Tab.1 and Tab.2.

Tab. 1 Impedances of the induction machine (simulation parameters)

Stator resistance / phase	0,5515	Ω
Temperature coefficient	0,00392	1/K
Reference temperature	20	°C
Operation temperature	95	°C
Stator leakage reactance	1,520	Ω
Main reactance	66,400	Ω
Rotor leakage reactance	2,310	Ω
Rotor resistance / phase	0,3750	Ω
Temperature coefficient	0,00400	1/K
Reference temperature	20	°C
Operation temperature	132	°C

Tab. 2 Nominal operation of the induction machine

Stator current	32.85	A
Power factor	0.898	
Speed	1462.5	rpm
Electrical input	20,443.95	W
Stator copper losses	770.13	W
Core losses	410.00	W
Rotor copper losses	481.60	W
Stray load losses	102.22	W
Friction losses	180.00	W
Mechanical output	18,500.00	W
Efficiency	90.49%	
Nominal Torque	120.79	Nm

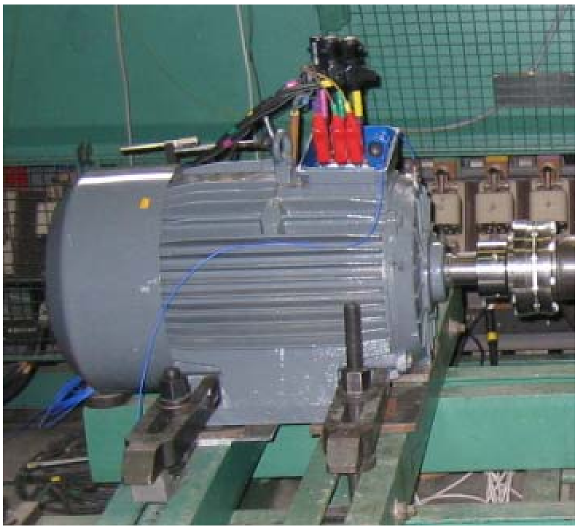

Fig. 4 Investigated asynchronous induction machine

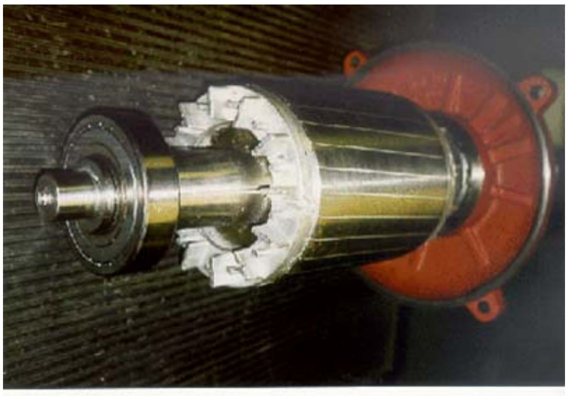

Fig. 5 Die cast aluminium rotor

Electrical measurements of the currents, voltages and electric power as well as the mechanical speed have been recorded every 10 seconds. For thermal measurements, 12 temperature sensors were attached to the machine and recorded every minute:

- 3 sensors each at the stator end-winding AS (drive end) and BS (non drive end) The temperatures of these 3 sensors have been averaged on each side (A and B).
- 2 sensors at the stator yoke The temperatures of these 2 sensors have been averaged.
- 1 sensor in a stator tooth
- 1 sensor in a stator slot
- 1 sensor each at air inlet and air outlet

To minimize the influence of heat dissipation due to mounting conditions, the machine was mounted with thermal insulation between feet and test bed.

The measured temperature of the air inlet has been prescribed for the simulation model to achieve the same conditions for measurement and simulation.

Fig. **6** shows the model of the whole drive. Additionally to the parameters summarized in Tab. 1 and Tab. 2, detailed geometric data of the machine were used to parameterize the thermal model.

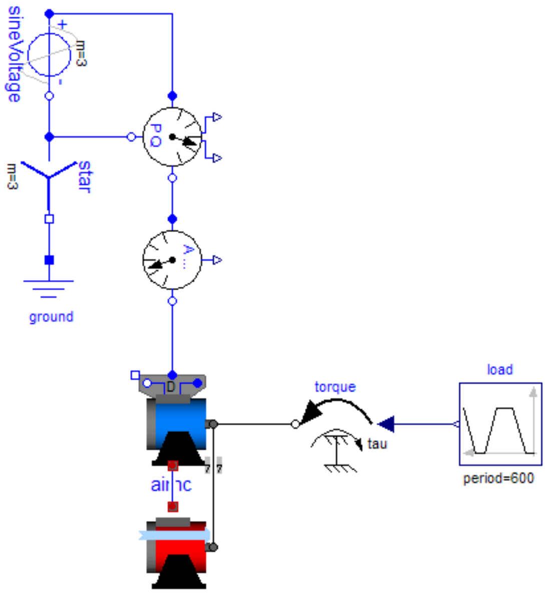

Fig. 6 Drive model

3.2 Test with constant load S1

The machine as described in 3.1 was supplied from the grid with constant voltage and frequency 400 V / 50 Hz; the drive was started from cold condition and loaded with constant nominal torque with a dynamometer. The test run has been carried on for 5 hours and 20 minutes until the recorded temperatures remained nearly constant.

The measured current consumption was nearly constant 32.9 A; the simulation result shows a current increase from 32.7 A in cold condition to 32.85 A at the end of the test run.

The measured speed of the machine starts from 1472 rpm in cold condition and decreases to 1461 rpm in hot condition whereas the simulated speed starts at 1474 rpm and decreases to 1462 rpm at the end of the simulation.

The figures Fig. 7- Fig. 12 compare measured and simulated temperatures:

- Temperature of stator slots
- Temperature of stator end-winding A-side (drive end) and B-side (non drive end)
- Temperature of stator teeth and stator yoke
- Air outlet temperature

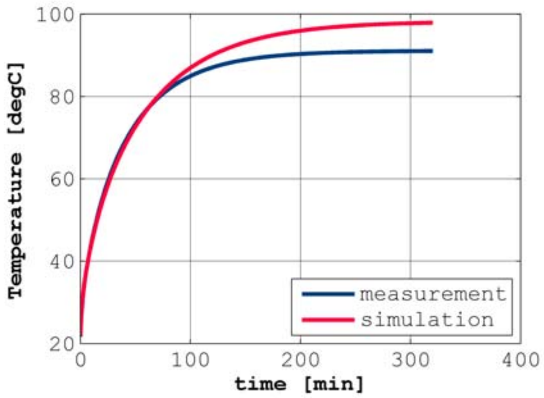

Fig. 7 Temperature of the stator slots

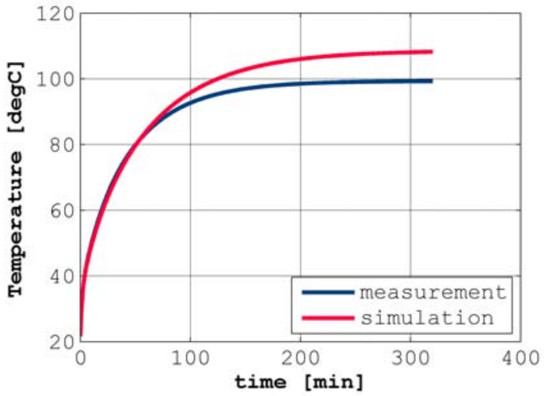

Fig. 8 Temperature of the stator end-winding (A-side)

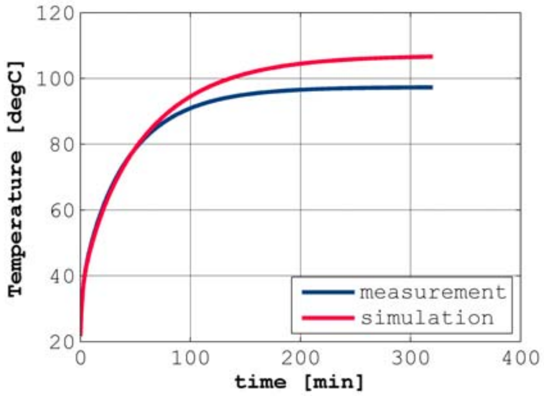

Fig. 9 Temperature of the stator end-winding (B-side)

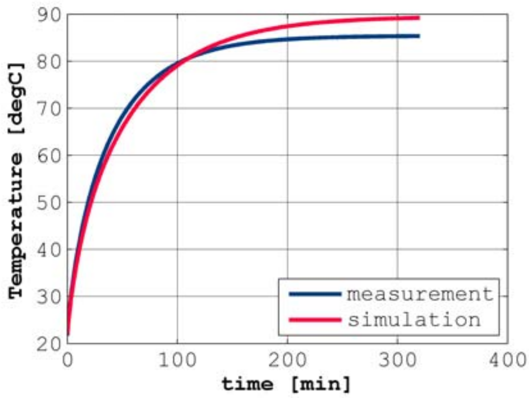

Fig. 10 Temperature of the stator teeth

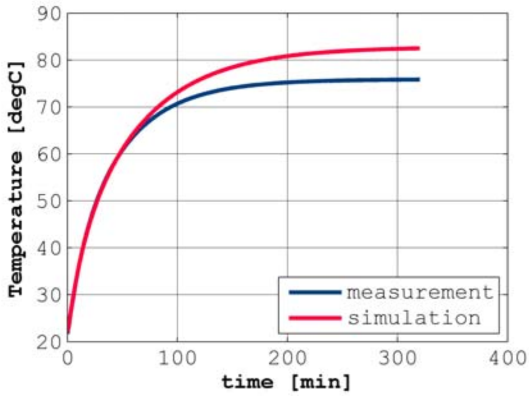

Fig. 11 Temperature of the stator yoke

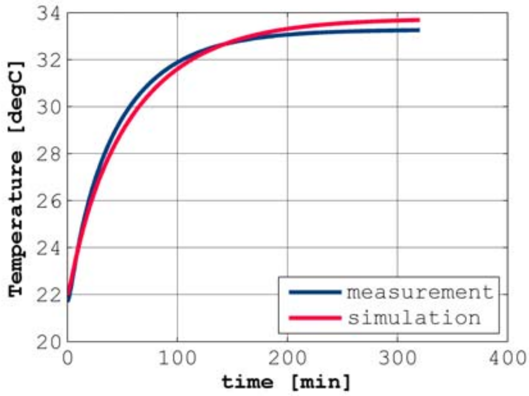

Fig. 12 Air outlet temperature

The deviations between simulation and measurement are between 4 and 9 K at the end of the test run. Additionally the gradients of the temperatures with respect to time show good conformance. The coincidence is satisfying which proves both the validity of the models as well as the parameters.

3.3 Test with intermittent load S6

The machine as described in 3.1 was supplied from the grid with constant voltage and frequency 400 V / 50 Hz; the drive was started from cold condition and loaded with intermittent load torque: 6 minutes of no-load operation, followed by 140% of nominal torque during 4 minutes, giving a load cycle period of 10 minutes as shown in Fig. 13.

The test run has been carried out for 4 hours and 26 minutes; the recorded temperatures have been watched at the beginning and the end of a load cycle. The test run was finished when the difference of compared temperatures at the beginning and the end of a load cycle was not greater than a threshold.

Fig. 14 shows how simulated speed decreases during the test run due to the temperature rise of the rotor. At the end of the test run, the speed at 140 % load was measured at 1443.5 rpm compared with 1444.5 rpm taken from the simulation.

The simulated current is shown in Fig. 15. No load current was measured at 11.9 A, compared with 10.3 A taken from simulation. For 140 % load both measurement and simulation show the same current of 46 A.

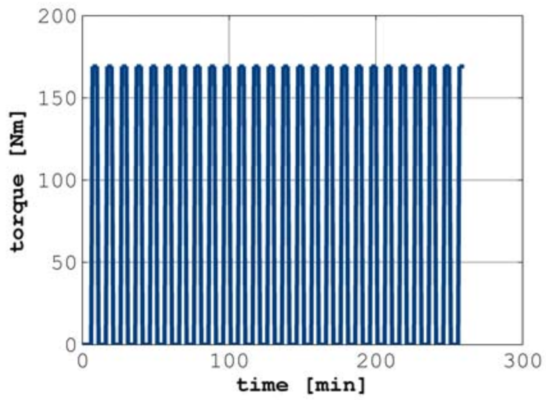

Fig. 13 Load torque (shaft) S6

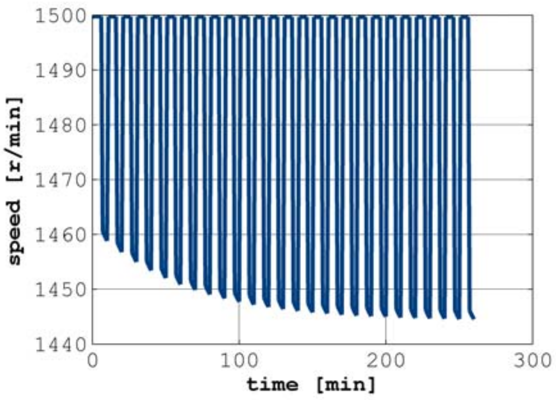

Fig. 14 Simulated speed

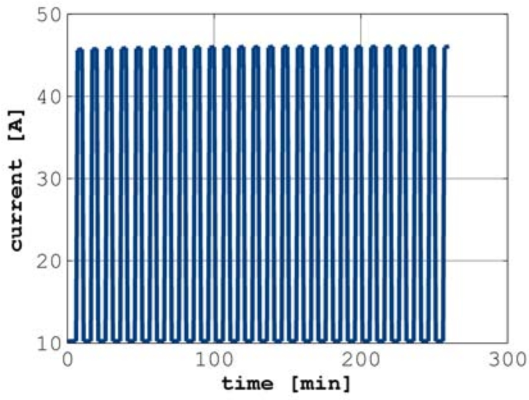

Fig. 15 Simulated current

The figures Fig. 16 - Fig. 21 compare measured and simulated temperatures:

- Temperature of stator slots
- Temperature of stator end-winding A-side (drive end) and B-side (non drive end)
- Temperature of stator teeth and stator yoke
- Air outlet temperature

The maximum deviations between simulation and measurement are between 3 and 7 K during the whole test run. Additionally the gradients of the temperatures with respect to time show good conformance. The coincidence is satisfying which proves temperature prediction is reliable even during an arbitrary load cycle.

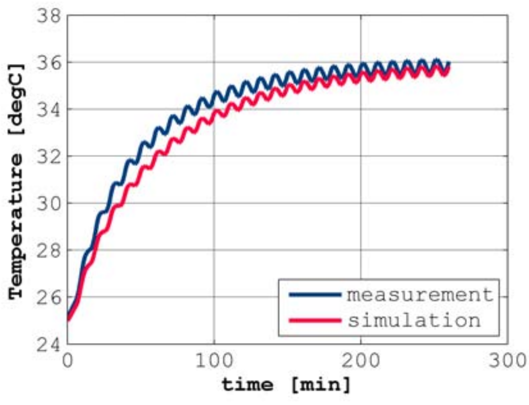

Fig. 16 Air outlet temperature

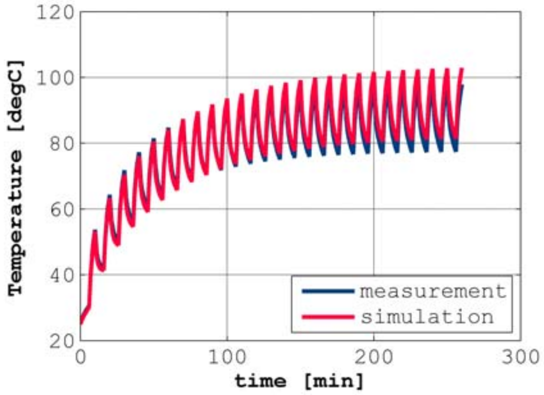

Fig. 17 Temperature of the stator slots

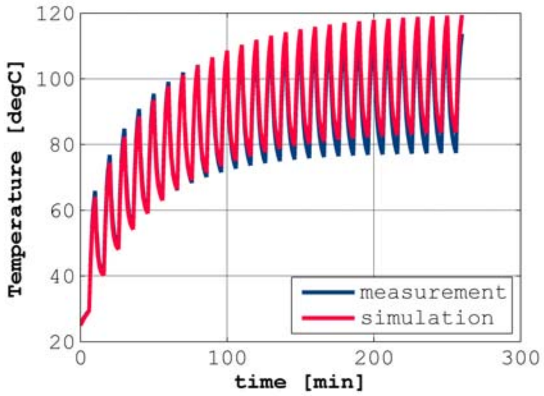

Fig. 18 Temperature of the stator end-winding (A)

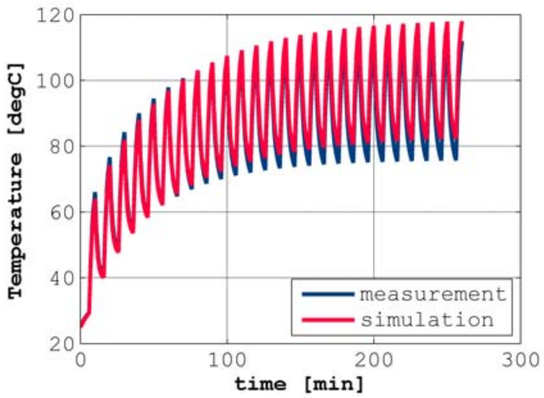

Fig. 19 Temperature of the stator end-winding (B)

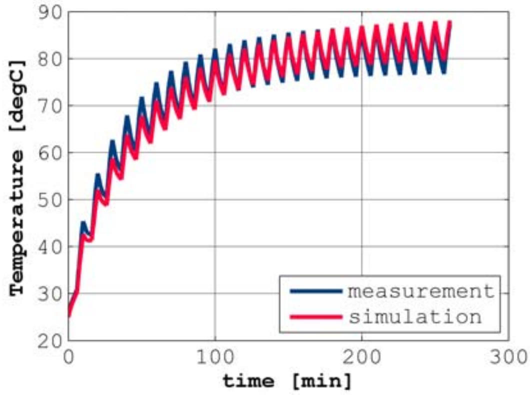

Fig. 20 Temperature of the stator teeth

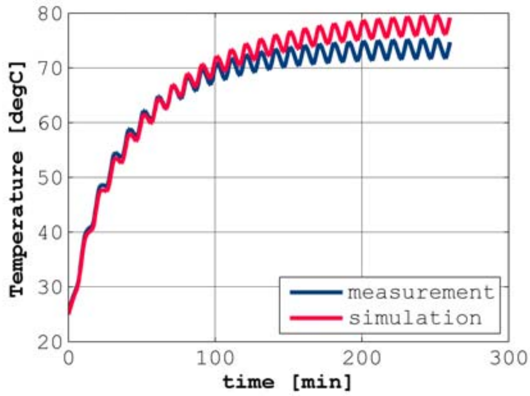

Fig. 21 Temperature of the stator yoke

4 Conclusions and outlook

Electro-mechanical ([2], [7]) and thermal models ([4]) of electric machines have been presented. Coupling and simultaneously simulating these models, the electrical and mechanical operation parameters as well as the temperatures of the investigated machine can be determined for a given load cycle.

The models were validated against measurement results, showing satisfactory accordance with detailed measurements. The remaining deviations between measured and simulated temperatures can be explained by the fact that the real machine shows a temperature distribution in regions where the simulation calculates an average temperature. The sensors measure a local temperature, however. Furthermore, determining the coefficients of heat transfer between stator end winding, rotor end rings, bearing shields, end parts of the housing and the inner air is a difficult calculation. Additionally the mounting of a temperature sensor never is perfect.

The performance of the simulation models is quite satisfying: On a 2 GHz double processor PC 10 seconds of real time consume approximately 1 second of simulation time.

Further work is planned to take into account additional losses caused by the higher harmonics of the voltage supplied by the inverter to the machine. Special care will be taken to keep the performance of the models.

Evaluating the simulation results, the design engineer is able to reveal shortages or excess of the machine in an early design phase. Appropriate measures can be taken to achieve an optimal design: The geometric and winding parameters of the active part can be corrected as well as an adaption of the cooling method can be considered.

5 References

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