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Thermal models of electric machines with dynamic workloads

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Electric powertrains are increasingly used in off-highway machines because of easy controllability and excellent overall efficiency. The main goals are increasing the energy efficiency of the machine and the optimization of the work process. The thermal behaviour of electric machines with dynamic workloads applied to is a key design factor for electric powertrains in off-highway machines. This article introduces a methodology to model the thermal behaviour of electric machines. Using a noncausal modelling approach, an electric powertrain is analysed for dynamic workloads. Cause-effect relationships and reasons for increasing temperature are considered as well as various cooling techniques. The validation of the overall simulation model of the powertrain with measured field data workloads provides convincing results to evaluate numerous applications of electric machines in off-highway machines.

Keywords
Electric powertrain, thermal simulation models, noncausal modelling

A growing demand of application for electric machines in off-highway machines and electric powered equipment leads to the utilization of compact, dynamic powertrain units. Besides the actual machine performance, thermal loads of the powertrain components have to be analyzed in detail to consider the thermal limitations. Nowadays in-field load cycles are taken into account to avoid oversizing of the electric machine and consequently to reduce weight, installation space and additional costs. The knowledge regarding heating processes of electric machines with alternating overload operations are indispensable. Unfortunately, manufacturer specifications for reliable performance in case of overload are often insufficient.

The overload capability of electric machines with dynamic workloads at high performance is proved as an essential advantage of electric powertrains. Compared to conventional powertrains electric ones are capable of providing short-time overload operating points. Only the temperature of components in the converter and electric machine are limiting the overload capabilities. Thus, by knowledge of thermal behaviour and a selective heat transfer, the rightsizing of electric components and consequently the entire powertrain are affected decisively. The main goal is to preserve the machine from invalid temperature treatment and to optimize overall machine utilization and, as a consequence to beneficially increase the work process. Thus, the Chair of Mobile Machines developed a method to evaluate thermal behaviour of electric machines with dynamic workloads. In the research project different levels of detail in thermal models are implemented to estimate the thermal behaviour of electric machines by means of simulation. The models are able to consider losses in different types and frame sizes of electric machines. Installation space, coolant and ambient conditions affect the machine performance, as well as mode of operation and dynamic workloads.

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Basically two different thermal modelling concepts are widely used. Firstly, the numerical methods such as flow simulation (CFD: Computational Fluid Dynamics) and, secondly, the network method with lumped parameters (Table 1).

The article presents a thermal modelling by means of network method and introduces a modelling and simulation method to consider thermal influences in electric powertrains. Due to the interconnection of electric and thermal models the network method with lumped parameter is applied to describe the powertrain.

Table 1: Methods of thermal modelling

Method	Advantages and disadvantages
Computational Fluid Dynamics (CFD)	+ high resolution of spatial temperature profiles
	+ variety of flow parameters can be recorded
	- time-consuming modelling and calculation
	- detailed design data necessary
Network method	+ rapid analytical calculation
	+ coupling with lumped parameter models
	- low resolution of spatial temperature distribution
	- assumption of flow conditions necessary

Heating of electric powertrain

Heating of the electric powertrain is attributed to the machine's individual power losses. Unlike inflexible electric power transmission for industrial applications with a fixed rotational speed, inverter supplied machines with variable speed output are used in off-highway machines. Reliable statements of machine power losses are only possible, when examining the system context. Thus the electric machine and the inverter have to be considered as one unit to include occurring interactions. Therefore, according to Figure 1, system boundaries are defined as DC link power at the inverter, mechanical output power of the machine and environmental conditions of the powertrain. Following the power flow from the supplying DC link through the inverter and the mechanical output on the shaft of the electric machine, various sources of power losses occur. Switching and conduction losses in the inverter reduce the inverter power output. Losses in the electric machine itself can be assigned to the assembly units stator and rotor. In the stator, current heat losses in the windings, iron losses in the stack of sheets and additional losses occur. In the rotor, also current heat losses and iron losses, as well as friction losses are taken into consideration.

Approximately 70–75 % of losses can be assigned to current heat losses caused by ohmic resistance in copper windings of the stator, further 15-20 % contribute to frequency-depending iron losses due to reversal magnetisation in the stator laminations (Hagl 2013). Losses occur in the form of current heat losses and are derived from the machine according to the thermal mechanisms of convection and heat conduction. An advanced machine performance is achieved regarding overload operation, by selective monitoring of winding temperatures. Thus, heating determines the system efficiency of the entire powertrain. The thermal management is decisive for the system's reliability and lifetime, taking individual components, installation conditions and environmental conditions into account. Consequently, a basic requirement to build up thermal models with different cooling methods is the capability of the modelled electric machine to consider losses. These electric machine models simulate corresponding losses by means of variable electrical resistance and magnetic reluctance. Therefore, losses may be displayed graphically in relation to current, voltage, frequency and magnetic flux (Pohlandt et al. 2014).

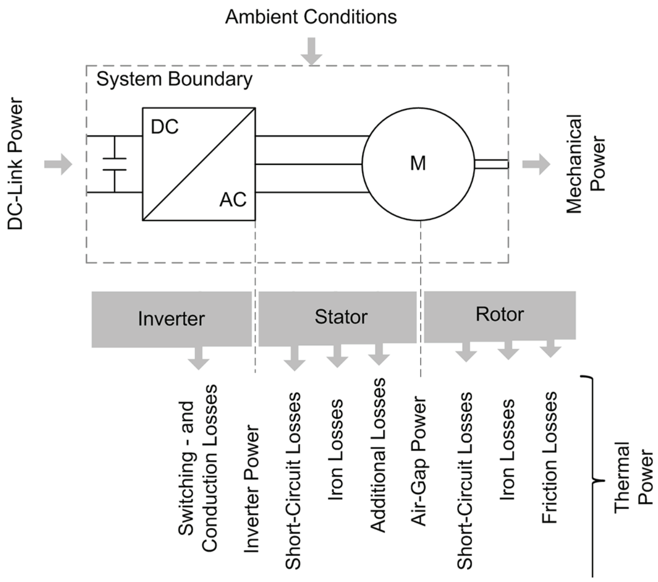


Figure 1: System boundary of the electric powertrain including assigned losses

Noncausal modelling concept to consider dynamic workloads

The simulation method of noncausal modelling is based on utilization of physical cause-effect relationships in simulation models. The system to be modelled is disassembled in single components and displayed using local differential algebraic equations (DAE) (Otter 2009). Depending on the physical domain, different potential and flow variables are used to describe state variables.

All potential variables have the same value in the connection points (Equation 1),

$$u_1 = u_2 = u_m \qquad \text{(Eq. 1)}$$

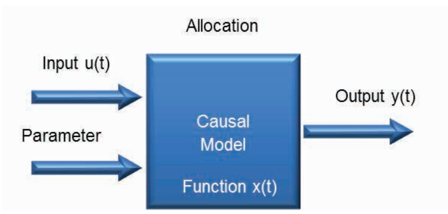
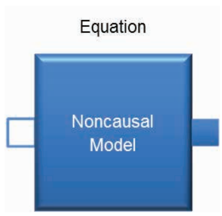
while, the sum of all flow variables equals to zero (Equation 2).

$$\sum_{n=1}^{m} i_n = 0 \qquad \text{(Eq. 2)}$$

Individual component models are linked with corresponding coupling equations via defined interfaces. Input and output variables are not defined explicitly. Therefore, the data flow is bidirectional. By hierarchical system integration, local variables automatically become global variables with corresponding assignment. With this, equation-based, transparent models are formed, which can be parameterised comprehensibly by the user. Modular design and links between components support a systematic development of extensive model libraries. Comprehensive equation systems can be solved efficiently by means of transformation algorithms and numerical integration procedures. Noncausal modelling is therefore suitable to simulate electric powertrains with dynamic workload and various motor-driven and generator-driven operating points. Moreover, the thermal systemic behaviour can be simulated. The presented simulation models below are implemented in the simulation environment Dymola with the object-oriented programming language Modelica.

Compared to the employed method, the connection between signal input and output of a signal-flow-oriented modelling is fixed. Thus, the model has a causal structure with unidirectional data flow, which cannot be reversed. A crucial disadvantage of causal modelling is the firm link between input u(t) and output y(t). An electric machine model with input values of voltage and current and outputs values of rotational speed and torque can commonly not be operated as a generator. For example Matlab Simulink is a causal simulation programme. Finally both above detailed modelling concepts are summarised in Table 2.

Table 2: Modelling concepts

	Signal-flow-oriented model	**Physical-oriented model**
Description form	State space $\dot{x} = f(x,u,t)$ $y = g(x,u,t)$	Descriptor form (DAE) $0 = f(\dot{x},x,y,u,t)$
Modelling concept	Causal  	Noncausal 
Relation	Allocation Input = Output	Equation Input = Output
Data flow	unidirectional	bidirectional

Cooling of electric machines

Numerous cooling techniques are realized to dissipate heat from the machine, following DIN EN 60034-6 (1996). Those techniques differ in the number of thermal cooling circuits, an appropriate cooling medium and the realization of coolant flow. According to Figure 2, depending on the cooling medium, gas-cooled machines, subdivided into air- and hydrogen-cooling, and liquid-cooled machines with water/glycol- or oil-cooling are differentiated.

Regarding a coolant flow, tube cooling, circuit cooling, internal cooling and surface cooling are distinguished, shown in Figure 3. For example surface-cooled machines with forced cooling and closed primary circuit are preferably used in vehicle applications with low to middle power requirements. This allows a full encapsulation of the machine interior to prevent dust and dirt ingress. Ribbed housings are installed to optimize heat transfer to the ambiance. A forced cooling is implemented by a separate fan, which is not mounted on the machine shaft, or by relative motion of the vehicle.

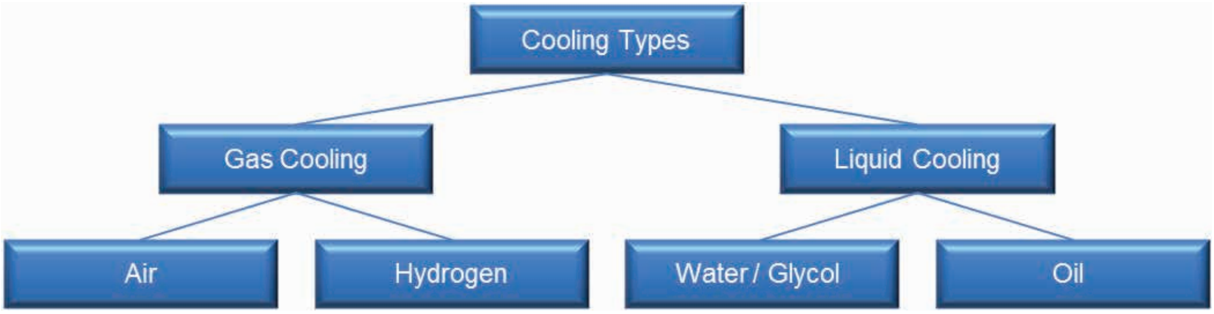


Figure 2: Coolant types of electric machines

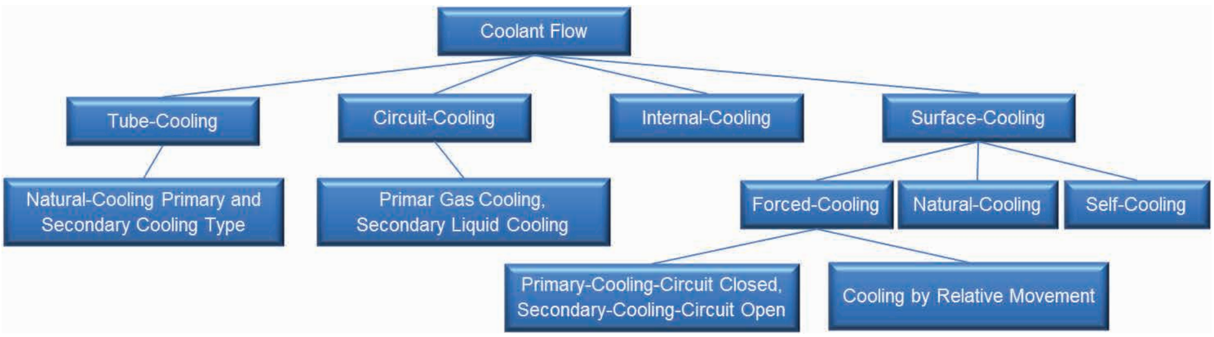


Figure 3: Coolant flow in electric machines

If higher performances are required, liquid-cooled machines are rather used. The difference of selected cooling types can be illustrated by coolant volume flow $\frac{dV}{dt}$ and permitted temperature increase $\Delta\vartheta$ referred to power losses (Equation 3) (Müller and Ponick 2005).

$$\frac{dV}{dt} = \frac{1}{\rho\, c} \frac{P_V}{\Delta\vartheta} \qquad \text{(Eq. 3)}$$

ρ: coolant density

c: specific heat capacity

The advantage of a liquid-cooled machine with water/glycol-mixture is the fact that reduced coolant is needed because of higher specific heat capacity (Table 3). As the main difference, the water/glycol-mixture has a high specific heat capacity c, which results in very small coolant quantities. Low flow velocity through small cross sections allow these coolant quantities to get very close to the heat source and, therefore, to reach a high effectiveness of the cooling technique.

Table 3: Comparison of required coolant volume flow of air and water/glycol

Coolant	Volume flow
Air	$0.83 \cdot \frac{P_V}{\Delta\vartheta}$
Water/glycol	$0.4 \cdot 10^{-3} \frac{P_V}{\Delta\vartheta}$

Method to model thermal behavior

Thermal modelling is based on real physical relationships in the machine. The temperature field is mapped as a discrete heat source network, whose junctions are linked with thermal resistances (Lehrmann 2006). The heat path may contain several heat capacities and heat sources. Heat resistances can be defined with simplified assumptions by the electric machine's geometry, heat capacities of used materials and heat transfer conditions at the interface to the coolant. Based on the thermal conductivity value λ (Equation 4), a thermal resistance R_{th} (Equation 5) for a material with homogeneous thermal conductivity can be defined similar to an electrical resistance with electrical conductivity σ. The thermal resistance reflects the connection between temperature difference $\Delta\vartheta$ and heat flow $\dot{Q}$ (Equation 6) (Table 4).

Table 4: Analogy observation of thermal modelling

Thermal	Electrical
Temperature difference	Voltage difference
Thermal resistance	Electrical resistance
Heat flow	Current
Thermal conductivity	Electrical conductivity
Heat capacity	Electrical capacity

The thermal conductivity value λ can be described by power loss P_V and temperature difference $\Delta\vartheta$ (Equation 4)

$$\lambda = \frac{1}{\Delta\vartheta} P_V \qquad \text{(Eq. 4)}$$

The thermal resistance R_{th} is described as (Equation 5)

$$R_{th} = \frac{1}{\lambda} = \frac{1}{P_V} \Delta\vartheta \qquad \text{(Eq. 5)}$$

In steady-state conditions, the power loss P_V is equal to heat flow $\dot{Q}$. Therefore, the thermal resistance R_{el} can be described corresponding to the electrical resistance R_{th} (Equation 6)

$$\mathrm{R_{th}} = \frac{\Delta\vartheta}{|\dot{\mathrm{Q}}|} \xLeftrightarrow{\text{Analogie}} \mathrm{R_{el}} = \frac{\Delta \mathrm{U}}{|\mathrm{I}|} \qquad \text{(Eq. 6)}$$

Also for the thermal capacity C_ϑ, a corresponding analogue can be described, using material properties (Equation 7).

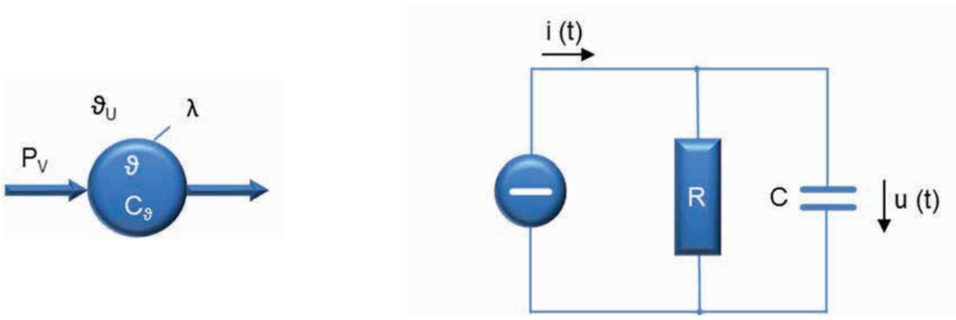
$$C_\vartheta = \frac{T_\vartheta}{R_{th}} = T_\vartheta \, \lambda \qquad \text{(Eq. 7)}$$

In the most trivial case, the electric machine is regarded as a homogeneous 1-body model with heat capacity and heat conductivity value with the surrounding, which is heated by power loss P_V of the machine.

The differential equation for the 1-body model is (Equation 8)

$$P_{VGesamt}\, dt = (P_{VStator} + P_{VRotor})dt = \lambda(\vartheta - \vartheta_A)dt + C_\vartheta d\vartheta \qquad \text{(Eq. 8)}$$

This approach allows extensive thermal networks to be build up just like discrete electrical networks (Figure 4) and to analyze transient temperature distributions under dynamic workload. Using a component analogy according to Table 4 and the examples of identical systems in Figure 4, the corresponding domain specific differential equations (Equation 9 and 10) can be specified to



$$\frac{1}{\lambda} P_V = \Delta\vartheta + C_\vartheta \frac{d\vartheta}{dt} \qquad R\, i(t) = u(t) + C\,\frac{du(t)}{dt}$$

Figure 4: Analogy of a heat source network and an electric network

$$\frac{1}{\lambda} P_V = \Delta\vartheta + C_\vartheta \frac{d\vartheta}{dt} \qquad \text{(Eq. 9)}$$

$$R\, i(t) = u(t) + C\,\frac{du(t)}{dt} \qquad \text{(Eq. 10)}$$

Individual power losses P_V of Equation 8 can be identified according to DIN IEC/TS 60349-3 (2011) by the machine's efficiency η (Equation 11):

$$\eta = \frac{P_{ab}}{P_{zu}} = 1 - \frac{\sum P_V}{P_{ab} + \sum P_V} \qquad \text{(Eq. 11)}$$

In principle, heating $\Delta\vartheta$ of the 1-body model follows an exponential function and reaches a final temperature t_B after a finite duration time $\Delta\vartheta_{End}$. At this operating point, a constant heat flow is equal to the power losses (FISCHER 2011).

For a constant coolant volume flow $\frac{dV}{dt} = \text{konstant}$ the temperature difference $\Delta\vartheta$ (Equation 12) is defined as

$$\Delta\vartheta = \Delta\vartheta_{\mathrm{End}} \left(1 - \mathrm{e}^{-t_B/\mathrm{T}_\vartheta}\right) \qquad \text{(Eq. 12)}$$

t_B: load duration

T_ϑ: heating time constant

with the end temperature $\Delta\vartheta_{End}$ relating to the coolant (Equation 13)

$$\Delta\vartheta_{\mathrm{End}} = \frac{\mathrm{P_V}}{\alpha\, O} \qquad \text{(Eq. 13)}$$

$\mathrm{P_V}$: power losses
α: heat transfer coefficient
O: surface

and a time constant T_ϑ of (Equation 14)

$$\mathrm{T}_\vartheta = \frac{c\, m}{\alpha\, O} \qquad \text{(Eq. 14)}$$

c: specific heat capacity

m: mass

A heating process with a steady-state temperature occurs when the machine is operated with constant workload for a sufficient time. These operating conditions are called continuous operation S1. The end temperature in steady-state condition must not exceed the temperature limit permitted for insulation of the windings. Obviously, the machine is able to increase performance for a certain time, without reaching the permitted maximum of winding temperature. But subsequently, the machine has to be stopped to cool down. These operations occur frequently and they are standardized ideally as operation S2 to S10 stated in DIN EN 60034-1 (2011). These operations are comprised of different load cycles with periodic character. After a certain load period, a downtime follows with currentless windings. At short time operation, operating mode S2, a load period with constant workload, in which a steady-state temperature is not reached, is followed by a time slot to cool down the machine. The identification is always made with information about a load duration, for example S2 30 min, for a load duration of 30 min.

Assuming, that the winding temperature is only depending on the heat current losses, short time dissipation $\mathrm{P_N}$ is obtained by continuous output $\mathrm{P_{S2}}$ (HAGL 2013).

$$P_{S2} = P_N \sqrt{\frac{1}{1 - e^{-t_B/T_\vartheta}}} \qquad \text{(Eq. 15)}$$

P_N: nominal power
t_B: load duration
T_ϑ: heating time constant

It is evident, that thermal modelling is a substantial criterion regarding dynamic workloads, when evaluating performance and designing an electric powertrain.

Basically, an electric machine cannot be simplified as a 1-body model, because cause-effect relationships of heating are more complex. Every single machine component heats up at different duration and is influenced by surrounding parts. Moreover, the converted energy changes with dynamic workload. Depending on the operating point, power losses of the components vary, which results in changing temperatures. Heat flows encounter because of local heating and therefore, temperature differences with various starting temperature profiles. Inside the machine, heat flows from an area with relatively high losses, and steep initial temperature gradient, into areas with comparably small gradient.

According to the design of noncausal modelling the data flow is bidirectional. The electric model of resistance R_{el} has temperature dependent power losses $P_V(\vartheta)$. These losses are transferred to the thermal model as heat flow $\dot{Q}$. In opposite direction, temperature ϑ is passed from the thermal model to the electric machine model, depending on the thermal resistance R_{th}, according to Figure 5. Any close meshed heat source network can be constructed by subdividing the machine into components, which share the power losses.

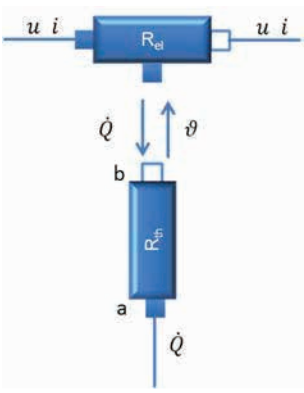


Figure 5: Model of a thermal and electrical resistance with bidirectional data flow

Verification of the simulation model

The verification of a thermal model is done by using a total simulation model (Figure 6) with continuous workload at the nominal operating point of the electric machine. The simulation setup consists of a validated machine model considering power losses, a thermal model and an air-coolant model. The results in Figure 7 show an exponential temperature increase of winding head temperature, ap-

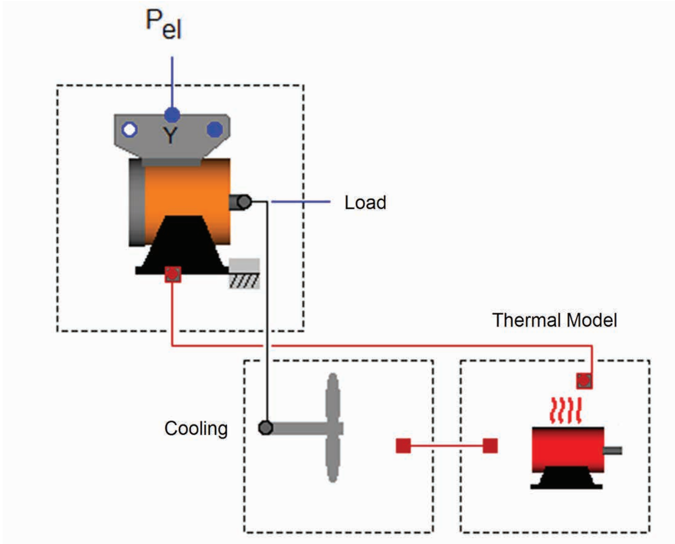


Figure 6: Noncausal simulation model of a self-cooled asynchronous machine

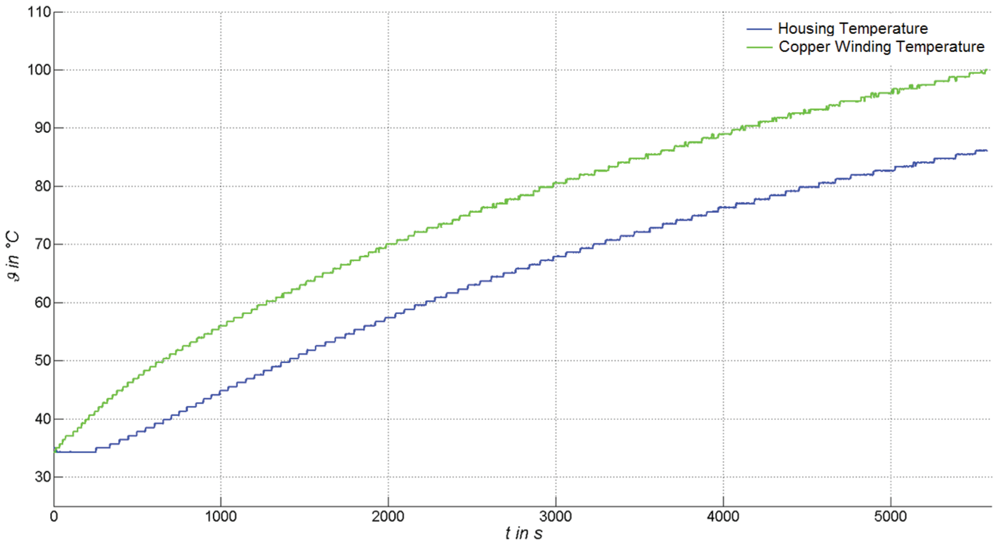


Figure 7: Simulated curves of initial temperature gradient of copper winding and housing

proaching a steady state (Equation 12). Moreover, a significant temperature increase of the housing temperature is observed. The temperature difference between housing and winding head indicates a heat flow from the machine interior to the surrounding. Different initial temperature gradients point to unequal share of losses. Copper windings, with proportional current-dependence, have a considerably higher share of loss than the stack of sheets, located in the nearby housing of the machine.

At a steady state condition (Figure 8) a constant heat flow is obtained which corresponds to the sum of individual power losses. As expected, the rotor windings and stator are exposed to the strongest thermal stress. The temperature gradient also follows the heat path towards the housing.

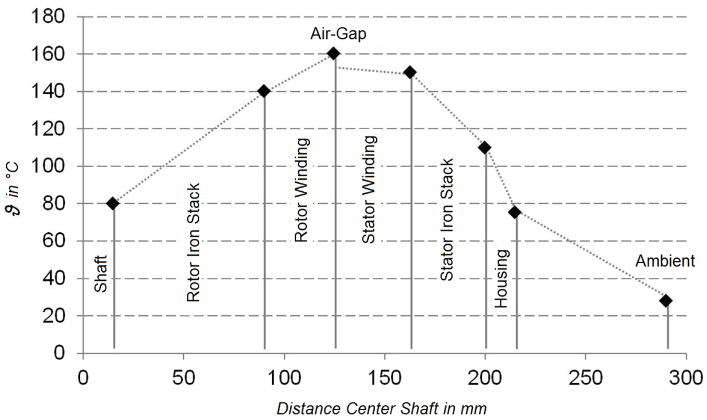


Figure 8: Stationary temperature distribution from the shaft centre simulated in steady state conditions

Identification of parameters to validate the machine model

To validate the overall machine model, consisting of verified individual sub-models, several test bench parameters are necessary. The parameters to configure the electric machine model, e. g. stator winding resistance and stator inductance, are determined by experiments of basic machine testing according to DIN EN 60349-2 (2007).

The required parameters of the thermal models are also specified with test bench results. The identification of heat resistances is made by a series of temperature measurements at constant workload. Thereby, the winding temperature can be recorded with either the resistance method, the thermometer method or with installed temperature probes. The temperature sensors were installed at seven critical measuring points to collect temperature profiles (Figure 9) of the copper winding, as well as temperatures near the stack of sheets and the housing.

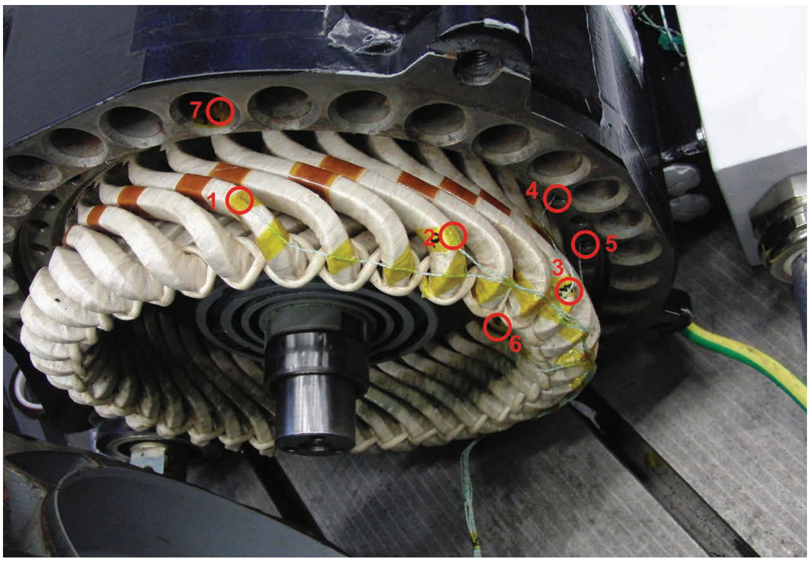


Figure 9: Temperature measuring points at stator winding for measurements of temperature profiles (photo: C. Pohlandt)

Different heat capacities of each component can be calculated from material parameters und related mass. Sufficient precision in parameter determination is given by manufacturer specifications regarding cross sections of the machine and material lists.

Validation of the machine model with dynamic workloads

The validation of the parametrized model (Figure 6) is performed on a powertrain test bench (Pohlandt und Haag 2014) by two mechanically connected machines (Figure 10 and Figure 11). The used electric machines are air cooled asynchronous machines with a nominal torque M_N = 700 Nm and a nominal speed n_N = 1780 rpm. The method to identify the parameters of the implemented simulation model is feasible with test bench measurements at a reasonable expense.

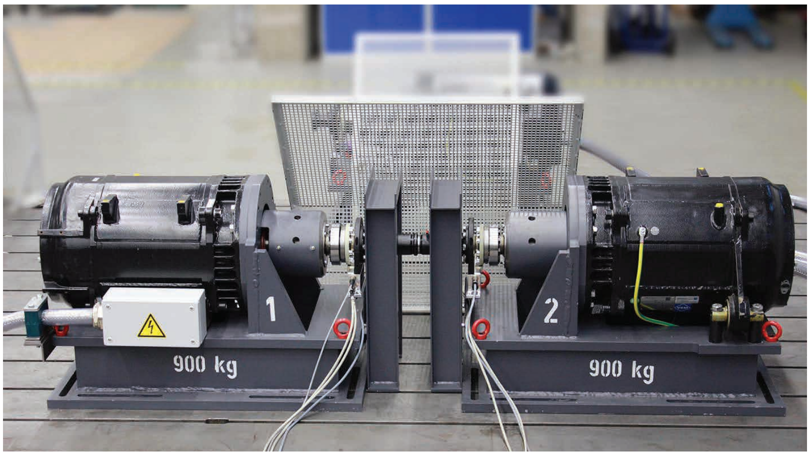


Figure 10: Mechanically coupled engines for parameter identification (photo: C. Pohlandt)

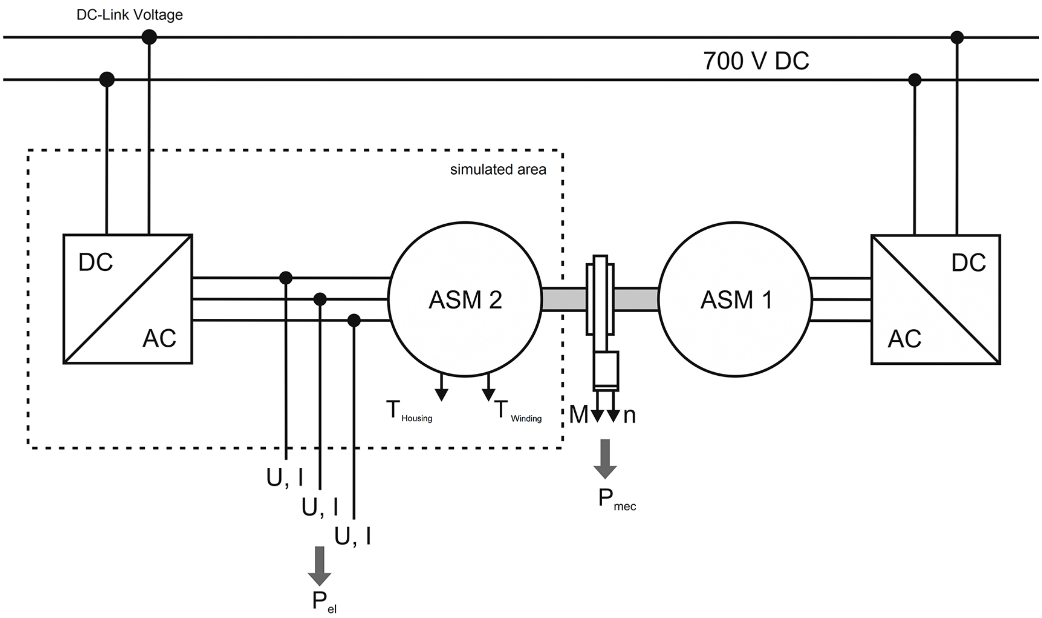


Figure 11: Schematic experimental setup to validate the simulation model under dynamic workload

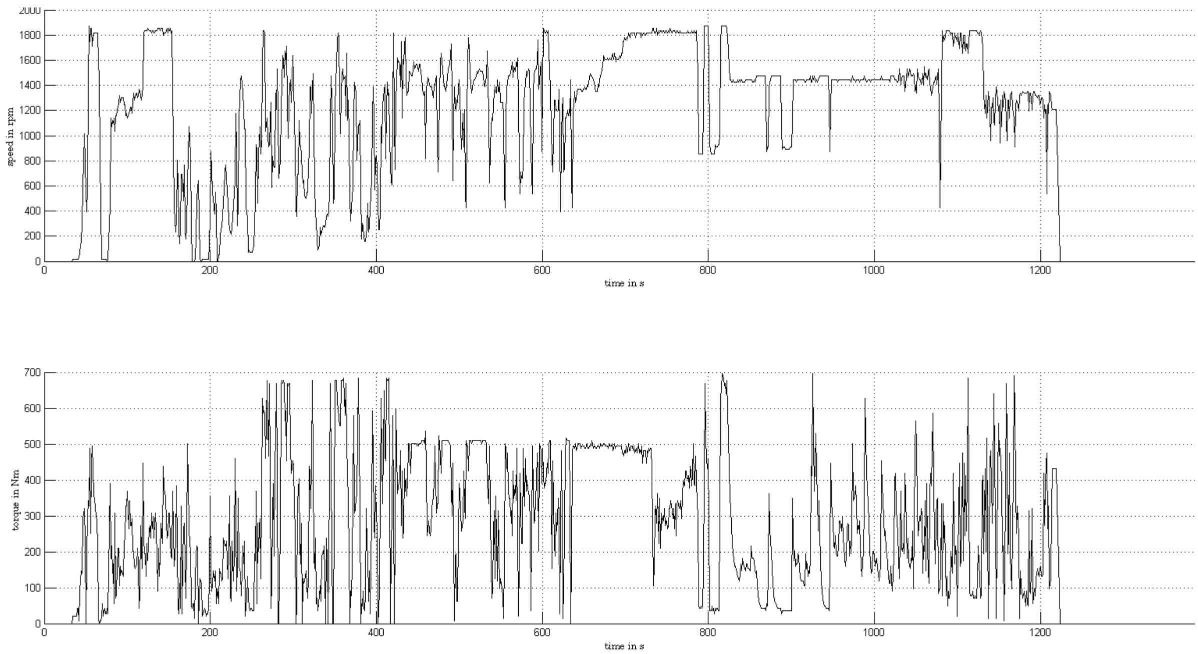


Figure 12: Dynamic load cycle to validate the thermal simulation model

The dynamic load cycle NRTC (Non-road Transient Cycle) for off-highway vehicles is applied for validation according to Directive 2004/26/EC (EU 2004). The cycle is used to determine current emission standards for diesel engines and results in high temperature at the after-treatment of exhaust gas. The cycle covers the entire operating range S1 of the electric machine with additional 5 % overload values. Characteristic data is summarized in Table 5. Because of dynamic and cyclical load a temporary heating and cooling process occur (Figure 13). This process is particularly distinctive, due to current-dependent ohmic losses in the windings during torque fluctuation. The test starts with a machine temperature equal to ambient temperature. It can be seen that the machine never reaches a thermal steady state. The thermal model corresponds well with the data, measured on the test bench. The temperature profiles of copper windings and stator stack of sheets have acceptable curves compared with test-bench measurement results. After a time t = 1238 s, the simulation model has a relative temperature difference $\Delta\vartheta$ in the copper windings of less than 5 K. The temperature in the stator stack of sheets is $\Delta\vartheta = 1$ K. So the results of the model performance are confirmed when using practical load cycles.

Table 5: Characteristic data of dynamic cycle

$n_{average}$ [rpm]	n_{max} [rpm]	$M_{average}$ [Nm]	M_{max} [Nm]	$P_{average}$ [kW]	P_{max} [kW]
1205.18	1900.05	274.04	690	39.45	136.49

Deviations during the cycle are explained with the number of resistances and heat capacities of the implemented heat source network. The heat resistance of the winding isolation is particularly significant in the heat source network. This resistance always has a high value. Therefore, noticeable temperature differences occur between the conductor material and the stack of sheets. Low electrical conductors like isolation material are even low heat conductors. Furthermore, concentric heat capacities with homogeneous temperature are summarized in the model. Taking these simplified assumptions into account a correction of the heat transfer resistances, compared with analytically calculated values, might be necessary.

As a conclusion, the presented thermal model is applicable to simulate the thermal behavior of electric machines in powertrains.

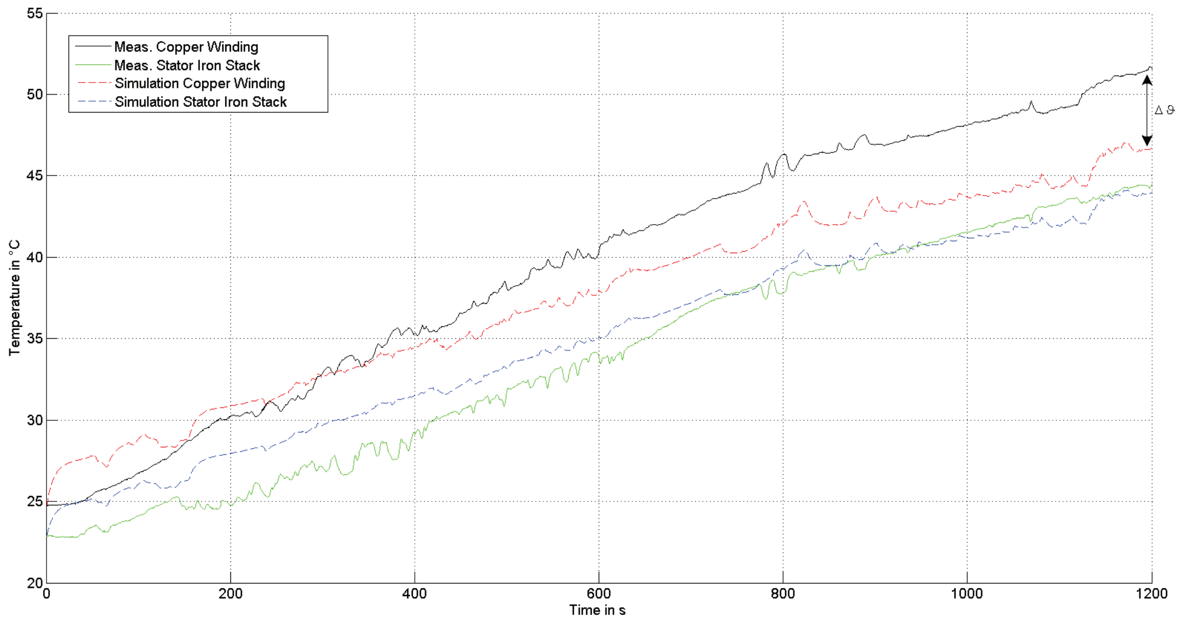


Figure 13: Comparison of the temperature profiles between simulation and measurement under dynamic workload

Conclusion

The temperature behaviour is a decisive characteristic value in practical utilization of electric machines. A significantly increased occupancy rate of the machine is achieved, when operating in dynamic workloads with short-term overload operating points. In this context, it is crucial not to exceed the temperature limits. The presented thermal models are able to predict the thermal behaviour of the electric machine in any practical load cycle. Potential weaknesses of the powertrain are already revealed in an early state of the development project and suitable countermeasures can be taken into account, without failure of the electric machine. Alternatives and extensions can be simulated and analyzed in detail for electric machine applications in off-highway machines. Especially, the noncausal modelling approach has proven to be successful allowing the user to model and precisely analyze complex powertrain topologies. A reusability of individual models is supported by the general interface structure of the presented simulation models. Thus, extensive model libraries can be developed. A thermal model based on lumped parameters provides appropriate solutions to predict the thermal load of a component. The limit of modelling depth is the resolution of the discrete heat source network. The basis for application-oriented research and development is provided by a consistent model library to simulate of electric powertrain components.

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