Efficient Electrothermal Simulation of Power Electronics for Hybrid Electric Vehicle

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Abstract

An IGBT module is an essential part of any hybrid electric vehicle. In turn, its thermal management happens to be crucial in order to reach high reliability coupled with high efficiency. In the present work, a methodology based on Krylov based model reduction is employed to generate automatically an accurate compact thermal model of the IGBT-module from a high dimensional finite element model. We present a complete design flow when one starts from an accurate finite element model, generates a compact dynamic thermal model and then uses it in a system simulator to develop the circuitry that is aware of thermal behavior of the system.

1. Introduction

In automotive applications, the requirements for the reliability of electronic systems are constantly increasing. This is the result of both increasing power required (50 kW for example) and higher integration, leading to higher junction temperatures. Thermal studies are fundamental for increasing the lifetime of the power inverters used in hybrid vehicles. One of their main goals is verifying whether reliable operating and uniform temperature fields are assured inside the used electrical switches. With these analyses, dysfunctions on cooling systems behaviour or non reliable thermal design of switch packages can be discovered.

The thermal concern of the inverter modules is extremely linked to their internal structure. Inverter modules are composed by several semiconductor devices (IGBT's and diodes) interconnected in parallel inside the same package in order to assure the high current ratings required in these applications. Those semiconductors are soldered on a DCB/DAB (Direct Copper/Aluminium Bonding) substrate which is again mounted on a water- or aircooled base plate.

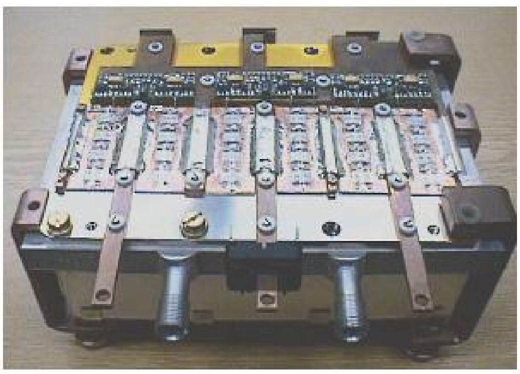

Fig. 1. Photo of an inverter power par for mild hybrid drive systems [1].

Simulation is an indispensable tool to speed up the development, especially in the multidisciplinary case such as an electrical drive [2, 3, 4]. One of the problems here is that system level simulation requires an accurate electro-thermal model of the devices.

It is possible to develop accurate thermal models with commercially available finite element packages. However, when it comes to transient or harmonic response simulation the computational time for a finite elements model becomes too long. Fortunately modern model reduction [5] allows us to generate dynamic compact thermal models automatically [6] and thus to cope with the high number of elements in finite elements (see Fig. 2).

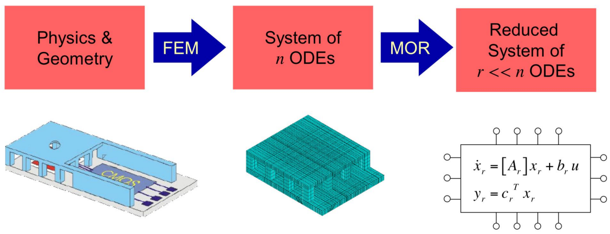

Fig. 2. Model reduction is an efficient means to enable system-level simulation.

In the present paper we describe a methodology as follows. First we use ANSYS Workbench [7] for accurate thermal modeling (section 1), then employ MOR for ANSYS [8] to automatically generate compact thermal models (section 2) and finally perform electrothermal simulation in CASPOC [9, 10, 11] (section 3).

2. Finite Element Modeling in ANSYS Workbench

In this paper we have used an IGBT module with three DCBs, as shown in Fig. 3 (the schematic is in Fig. 8). Each DCB has four IGBT and six diodes. The water cooling on the bottom part of the plate has been modeled through convection boundary conditions, when values of the film coefficients have been transferred from CFD simulation in ANSYS CFX.

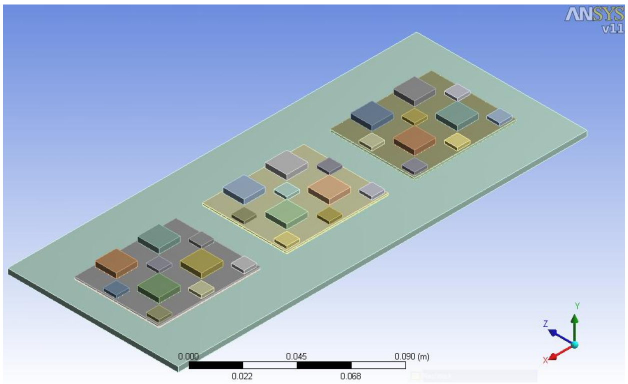

Fig. 3: Thermal Model of the IGBT module in ANSYS Workbench [7].

The thermal cross talk between different DCB modules is shown in Fig 4 when the power dissipation has been applied to the middle DCB only. It shows that it is important to take this effect into account also during system level simulation.

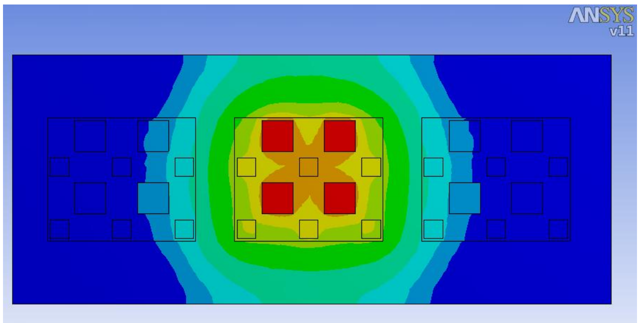

Fig. 4. The thermal cross talk between the neighboring DCPs.

The goal of thermal simulation is to determine the maximum temperature of the device as a function of time. However, in order to make an efficient compact model, one has to define outputs as a linear combination of the state vector. In several separate simulations, we have found that a middle point on the upper surface of each device can be used as a good approximation for maximum temperature.

3. Generating Compact Thermal Model with MOR for ANSYS

Model reduction based on the Arnoldi algorithm was shown [6] to be an efficient mean to generate dynamic compact thermal models. Its idea is shown in Fig. 5.

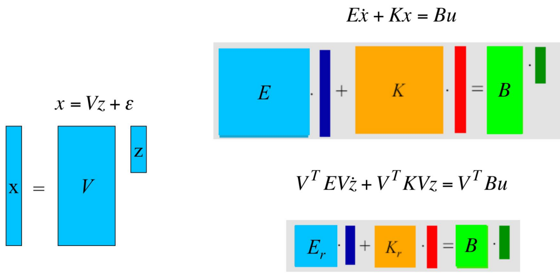

Fig. 5: Model reduction as a projection.

After the discretization one obtains a system of ordinary differential equations (top equation right in Fig 5) where E and K are system matrices related to heat capacity and heat conductivity accordingly. The input matrix B prescribes how power from the input vector u is distributed along the state vector x that contain unknown temperatures. It happens that the high dimensional state vector x can be well approximated by a low dimensional vector z (left in Fig 5) where the project matrix V is computed as a Krylov subspace by the Arnoldi algorithm [6]. Projecting the original equation on the low-dimensional subspace V allows us significantly to reduce the dimension of the original system developed in ANSYS (bottom equation right in Fig 5).

MOR for ANSYS [8] reads system matrices direct from ANSYS Classics or ANSYS Workbench [7] and performs model reduction – see Fig. 6. At the end, it writes system matrices of the reduced system in the form that can be used directly in CASPOC [9].

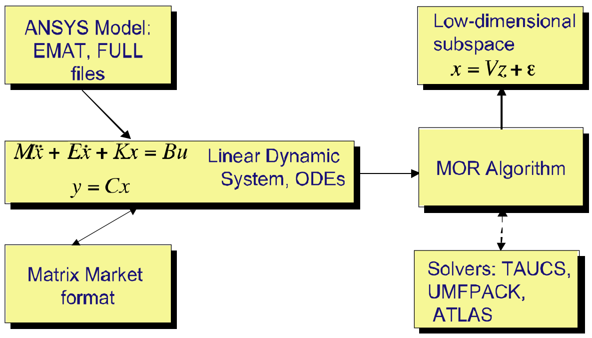

Fig. 6: MOR for ANSYS block scheme.

In our case, there are thirty heat sources defined in ANSYS Workbench. In this case, MOR for ANSYS uses the superposition Arnoldi algorithm [12] to make sure that in the reduced system each of thirty devices can be turned on and off independently. At the same time, the thermal cross talk effect is preserved very accurately during model reduction.

An important question is the choice for the dimension of the reduced system. It is understandable that the bigger the dimension, the more accurate is the reduced system. MOR for ANSYS employs an error indicator [13] to determine the dimension the reduced model automatically based on given precision. In our case it happened that the reduced model of order 300 (10 degrees of freedom per input) is enough.

The time for model reduction in our case is dominated by writing FULL files with system matrices and load vectors and is given in Table 1. For each load vector it is necessary to generate one own FULL file, because the FULL file can hold only one load vector. However the time for model reduction even with the communication overhead is relatively small, especially if one compares it with the time necessary to run transient thermal simulation in ANSYS Workbench. It should be noted that the dimension of a reduced system does not depend on the dimension of the original system – for all the cases in Table 1, the dimension of 300 is enough to accurately describe the transient response.

Table 1: Total time in second necessary to perform model reduction

Dimension of the model, DoF	Time for writing FULL files	Time for model reduction
15820	62	10
30048	118	19
172500	425	157

The comparison for transient simulation in ANSYS and with the reduced model is given in Fig 7 for one output for the step response when the input power of 100 W. The difference is just negligible and it is close to the line thickness.

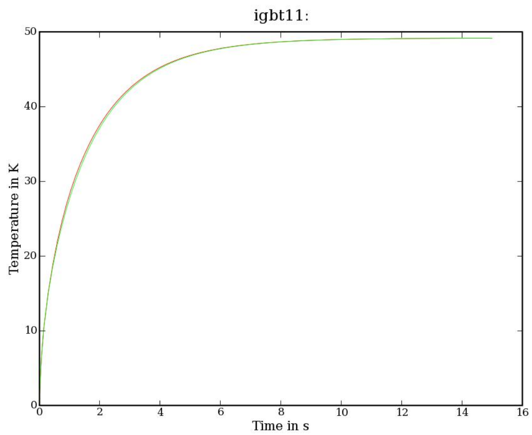

Fig. 7: Temperature rise computed in ANSYS for the full scale model (red line) and with the reduced model (green line).

The communication between ANSYS Workbench and MOR for ANSYS is as follows. A user defines named sets in the module *Simulation* in Workbench. Then the script in Workbench takes these names as input, generates necessary FULL files, defines outputs as discussed in the section above and then runs MOR for ANSYS.

4. System Level Simulation in Caspoc

In this section we first introduce Caspoc as multilevel simulator, then we discuss modeling of electrical drives in Capsoc and then we will consider the model relevant to the simulation of the IGBT module considered above.

Multilevel simulation in Caspoc

Caspoc was developed to simulate power electronics and electrical drive designs ranging from DC-DC circuits to complete controlled electrical drives, where the problem of the different time constants is solved. In power electronics and electrical drive simulations, the principle cause of short time constants is the fast switching of semiconductor devices such as diodes, MOSFETS and IGBTs. Switching takes place on the nanosecond scale, while the overall system response is on the millisecond scale for the control, while on second's scale for the mechanical drives. Considering all semiconductor-switches as ideal eliminated this time-scale problem in Caspoc. A special solver was developed for Caspoc capable of handling the state events and inductor turn-off in switching circuits. Figure 8 shows a typical voltage source inverter as required in automotive drive-train applications.

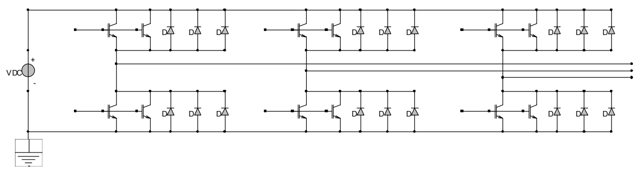

Fig. 8: An inverter model in Caspoc. This scheme corresponds to the thermal model shown in Fig. 3.

For the inverter as shown in Fig 8, the precise behavior of the semiconductor switch has an impact on the overall system performance. The efficiency of the total drive depends on the behavior of the single components inside the inverter. Since the influence is mostly small, use is made of ideal semiconductor models. If a more detailed non-linear dynamic model would be used, more detailed switching waveforms could also be analyzed. This detailed analysis is best carried out in a separate simulation of a single switching leg.

An important part of the inverter design is to evaluate the interaction of the semiconductor's dynamic characteristics with parasitic parameters such as bus-bar inductance and capacitance. Figure 9 shows a detailed model for an IGBT gate driver where also the parasitic components of the bus bar are modeled.

The turn-on and turn-off waveforms are shown, and from these waveforms the non-linear behavior of the switches can be seen. Losses arising during the switching events are warming the package and therefore cooling has

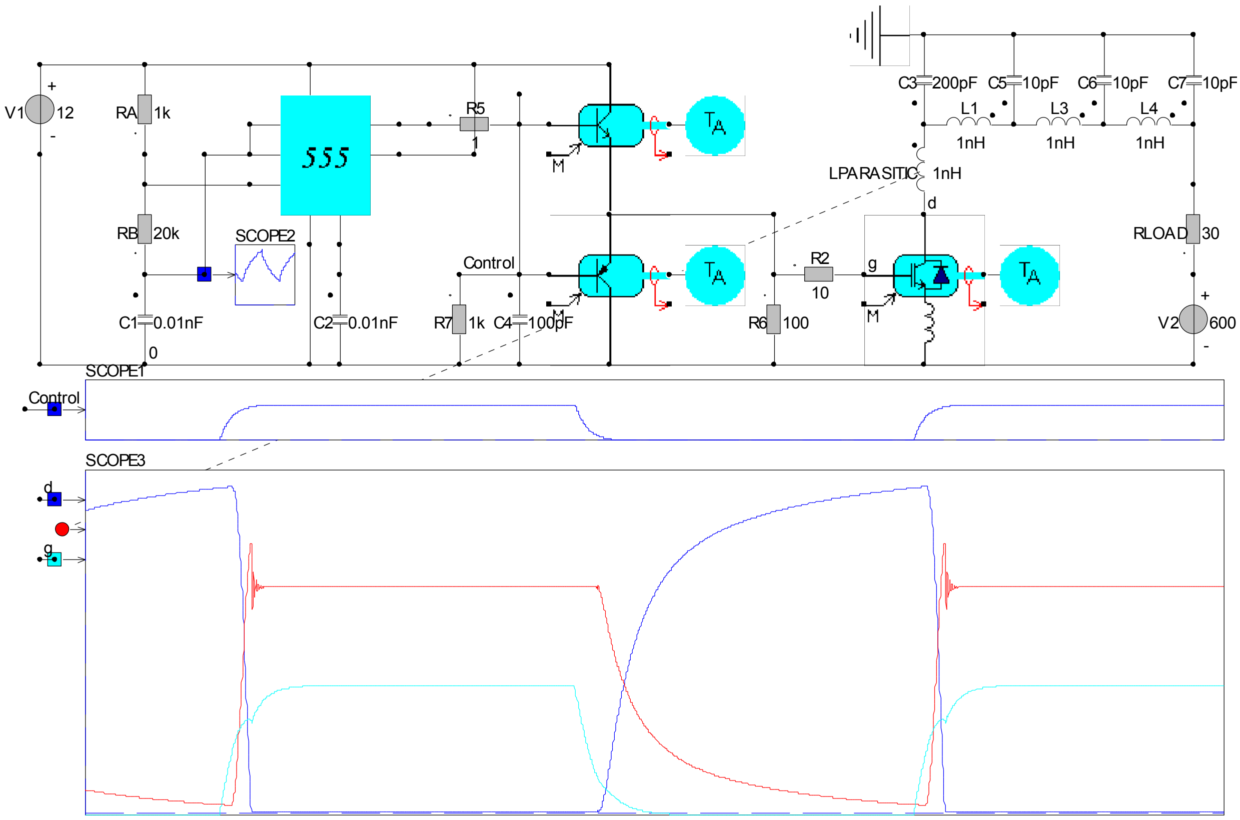

Fig. 9: Gate driver, IGBT and parasitic bus bar components

to be applied to keep the semiconductor junctions temperature below the maximum temperature. In Caspoc various models are available. The ideal switch models, loss-predicting models and also the detailed non-linear dynamic models are available. Behavioral models are included to allow simulation of diode, SCR and GTO reverse recovery as well as MOSFET delay times and IGBT turn-off tail currents.

The detailed models in Caspoc are available for IGBT, MOSFETs and Diodes. These models can be connected to thermal models and the parameters inside the models are temperature depending. Also the detailed models are required to model the influence of the bus bar components on the switching waveforms.

Since the detailed models require long simulation times and the ideal models are not giving good enough or accurate simulation results regarding efficiency and thermal management, special loss predicting models are developed. These models are used in this research and are explained below.

Electrical Machine Models

Electrical machines can be modeled in various ways. In the first place a simple linear model can be used to study the overall system performance. The next step is to include a more detailed model of the electrical machine in order to study the influence of saturation and other non-linear behavior. Models for the Permanent Magnet Synchronous Machine and Induction Machine can be found in [2, 3, 4] and will be investigated in a future work. The efficiency of a drive train for example is depending heavily on the efficiency of the inverter. Therefore the losses in the inverter have to be investigated and the inverter has to be designed such, as to minimize those losses. In the next section we will have closer look at these losses and how they can be modeled in the simulation.

Temperature depending models

Figure 10 shows an example of the temperature dependence of the forward characteristic of a semiconductor. In this figure a Light Emitting Diode (LED) is used for demonstration purpose. Here the on state voltage as well as the on state resistance are depending on the junction temperature.

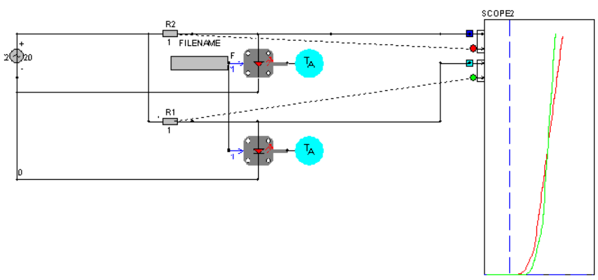

Fig. 10: Temperature dependency of the LED forward characteristic.

The upper LED is connected to an ambient temperature of 120 degrees Celsius, the lower LED is operating at room temperature. A sinusoidal voltage drives both LED's, allowing to see the full characteristic in the simulation. The on state voltage of the hotter (upper) LED is smaller, while its on resistance is larger compared to the LED at room temperature. From this figure we can clearly see that the on-state characteristic depends on temperature and therefore the overall efficiency of an inverter depends on the temperature of each semiconductor inside the inverter.

Thermal cycling and loss predicting models

An analysis of thermal cycling is required to predict the lifetime of a component. Also important is that the thermal cycling of the semiconductor can simultaneously be simulated with the electric and thermal circuit, from which the temperature dependent losses are determined. Converter efficiency, cooling requirements and heat sink dimensions are in this way calculated. If only the thermal cycling is of interest, the detailed semiconductor models are not always required. In Caspoc loss-prediction models can be used that replace the detailed non-linear dynamic models, see Fig 11. Using these loss-predicting models, the thermal cycling and the temperature dependent losses are approximated on basis of parameters and characteristics in data sheets provided by the semiconductor manufactures. These loss-predicting models require no dynamic non-linear models, but have a high simulation speed because they are based on ideal switching models. The losses in the switches are approximated based on the temperature, gate driver data, computed currents and voltages of the ideal switches. The data sheet provides the parameters and/or characteristics for the conduction and switching losses.

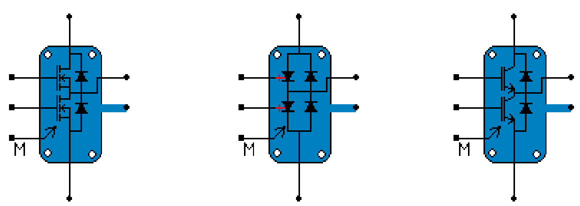

Fig. 11: Loss predicting models for MOSFET, IGBT and Diode.

The loss predicting models replace the detailed semiconductor models in a power electronics simulation when the overall system simulation is of importance. The detailed waveforms are now approximated by ideal waveforms, since an ideal semiconductor switch replaces the detailed dynamic model of the switching semiconductor. The advantage is the increased simulation speed.

Figure 12 below shows the simulation of the inverter from Fig 8 connected to the thermal model. The thermal model is represented by one block that has as input the reduced order model from Ansys. Since there are 30 semiconductors in this inverter, the reduced order model also has 30 thermal connections. These thermal connections are shown on the left side of the block. The connections on the right side are only used for displaying the temperatures of the thermal nodes.

The model of the inverter is split up into three separate models, where each model includes one switching leg of the inverter (one DCB in Fig. 2). Inside each switching leg model, there are 4 IGBTs modeled and 6 diodes as shown in Fig 8. The losses in these models are predicted based on the given data sheet parameters Eon, Eoff and Err (reverse recovery loss). These parameters are temperature depending and therefore the losses are depending on the temperature of each semiconductor.

The left side connections of the switching leg model are the four gate connections (G), since we have 2 high side and 2 low side IGBT switches. The thermal node of each semiconductor (IGBT or diode) is shown on the right side of the switching leg block and is directly connected to the thermal MOR model. The thermal nodes in the switching leg model are identified by the color of the component. In this way a distinction can be made between high and low side and diode and IGBT.

The MOR model has labels identifying to which thermal node in the ANSYS model they belong. The user can define these labels in ANSYS, and when the model is exported form ANSYS and imported into CASPOC, the labels identify the thermal connection of the MOR model.

The model in figure 12 shows the simulation of an inverter driven induction machine drive for 500 ms and one can see that the start up by itself takes less than 250 ms. For this simulation we have specified the nominal power of the machine (400 V/4 poles) of 20 kW, the mechanical load as quadratic and equal to 19 kW at the nominal speed. The speed-torque characteristic during the start-up is shown in Fig 13. The inverter has Pulse Width Modulation (PWM) and is directly controlling the gates of the inverter. The influence of the PWM harmonics on the produced torque is clearly visible in figure 13. In this simulation the control is open loop.

The IGBT and diode junction temperatures are displayed in figure 14. The temperature rise for this load is moderate and starts from the ambient temperature of 25 degrees Celsius. Only the first 20 junction temperatures are displayed in figure 14.

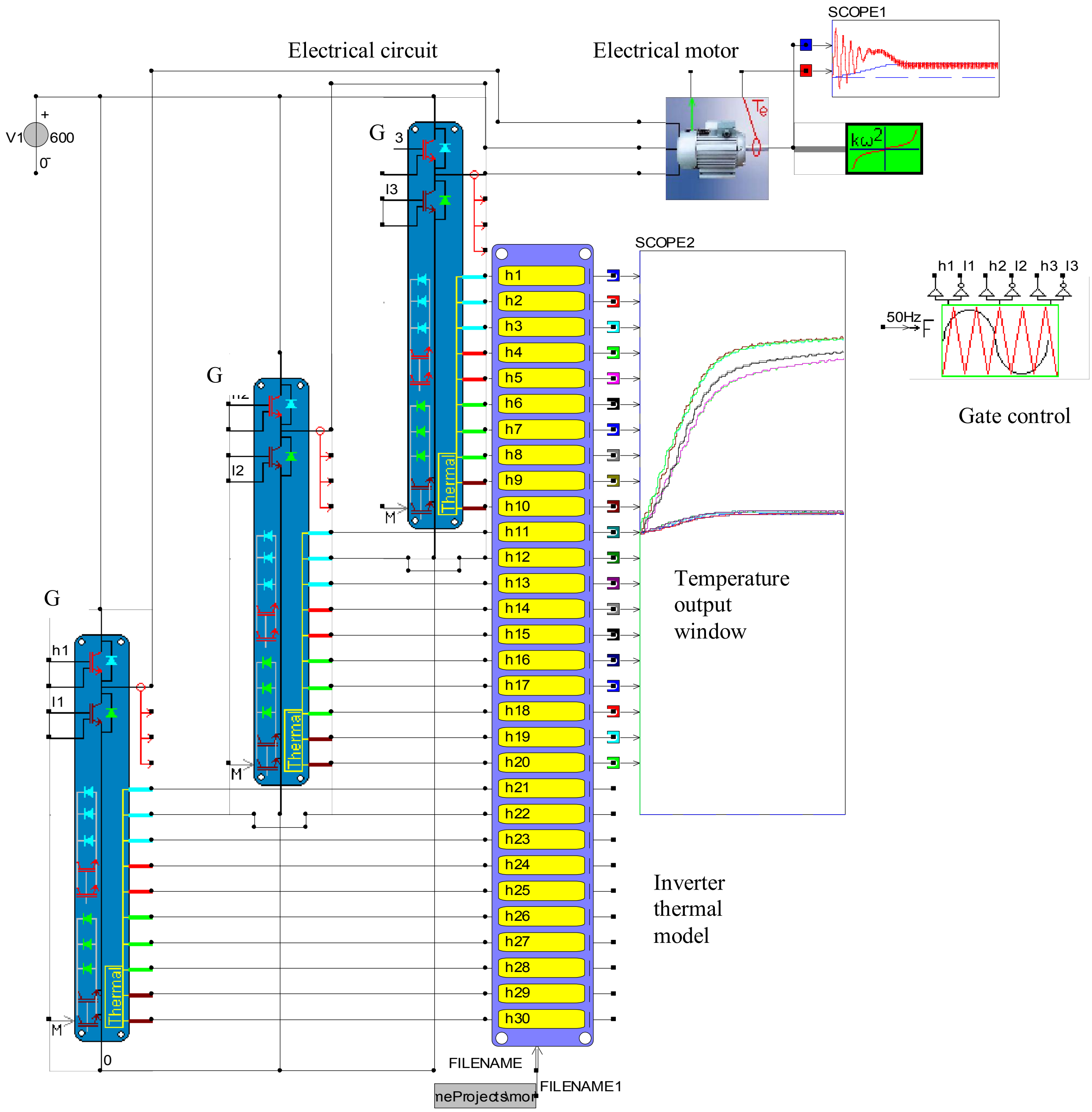

Fig. 12: Inverter thermal compact model obtained after model reduction in Caspoc.

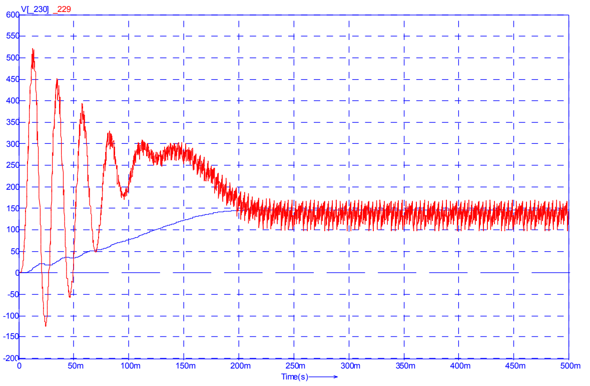

Fig. 13: Start up of the induction machine with the inverter. Voltage (blue) and torque (red) happened to have the same numerical values shown on the y-axis.

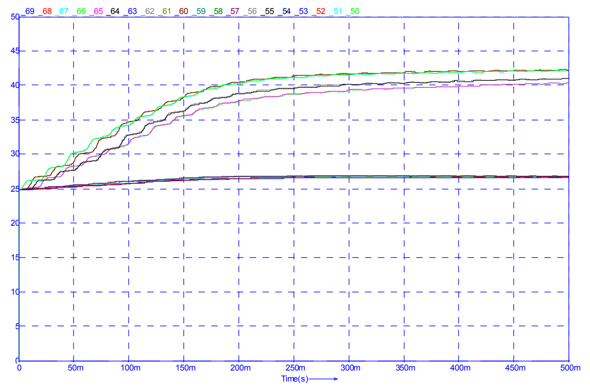

Fig. 14: Temperature rise on the IGBT during start up.

5. Discussion

We have demonstrated that modern development in the area of approximation of large-scale dynamic system [5] allows us to generate accurate dynamic compact models in completely automatic fashion. We have presented an environment consisting from ANSYS Workbench, MOR for ANSYS and Caspoc that makes electrothermal simulation feasible for design purposes.

Further steps should be the implementation of a non-uniform heat transfer coefficient in Ansys Workbench and transferring it to Caspoc.

Another improvement should be the calculation of losses depending on the inverter module construction. Parasitic inductances could be therefore measured/calculated and implemented in Caspoc.

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