Effective Electrothermal Simulation for Battery Pack and Power Electronics in HEV/EV

Evgenii B. Rudnyi

CADFEM GmbH, Grafing b. München, Germany, erudnyi@cadfem.de

Summary:

Thermal management is an important part during the development of a hybrid or electrical vehicle. This concerns several components in the electrical network of a car, the most important being power electronics and a battery pack. Electrothermal simulation is required at the system level in order to choose the best regime that complies with all thermal requirements and an important problem is how one can quickly obtain a compact but accurate thermal model needed at the system level. A methodology based on model reduction is suggested. One starts with an accurate thermal model developed with finite elements (ANSYS Workbench) then reduces the model by means of implicit moment matching (software MOR for ANSYS) and finally couples the reduced thermal model with an electrical model in Simplorer. Three case studies are presented: 1) a Freescale chip with MOSFETs, 2) IGBT converter, 3) a battery pack.

Keywords:

Electrothermal simulation, model order reduction, finite element model, power electronics, MOSFET, converter, IGBT, battery pack

1 Electrothermal simulation

Electrothermal simulation at system level is joint simulation of electrical and thermal parts (see Fig. 1). The parameters of the circuit depend on temperature and at the same time the circuit produces power dissipation. On the other side, the thermal part takes power dissipation and evaluates temperatures in the system according to the heat transfer laws.

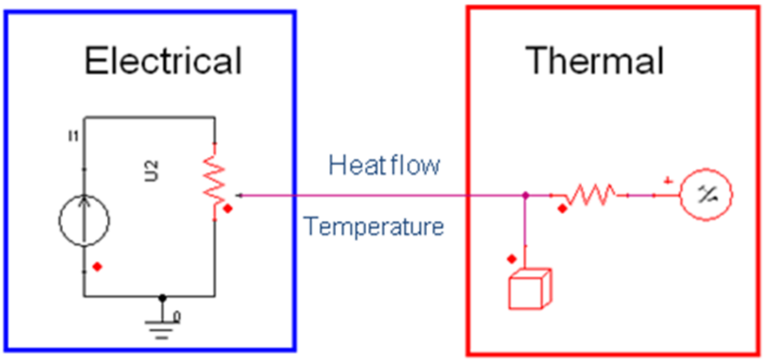


Fig. 1. Simple electrothermal simulation

As a simple example, let us take a temperature dependent resistance shown on the left in Fig 1. When the current passes through the resistor, it generates heat that in turn goes through a thermal mass and thermal resistor (on the right in Fig 1). The temperature of the system goes back to the electrical model of the resistor and thus we have two-way coupled electrothermal simulation.

The thermal model in Fig 1 is very simple and the question arises how one can develop it in the general case of complex geometry. In this case, a finite element modeling would be the best solution because with available software thermal modeling has already become a routine procedure. In principle, one can directly convert a thermal model into a circuit model (there are interesting examples in [1]). After the discretization by the finite element method one obtains an equation

$$E\dot{T} + KT = F \qquad (1)$$

that can be considered as an electrical network where the vector *T* will be equivalent to unknown voltages, the matrix *E* will be a capacity matrix and the matrix *K* the resistance matrix. The problem along this way is that the vector *T* is usually high-dimensional, say several hundred thousand degrees of freedom, and hence the Eq 1 is not compatible with system level simulation because of its large dimensionality.

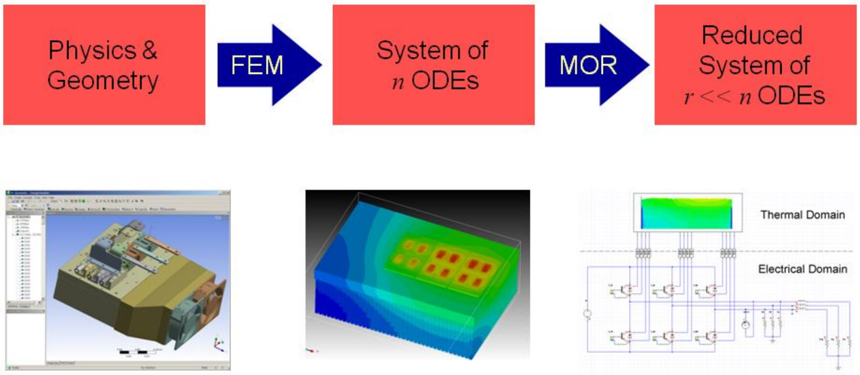


Fig. 2. The idea of model order reduction

Model reduction [2] allows us automatically to reduce the dimension of Eq 1 preserving at the same time good accuracy of the dynamic response (see Fig 1). In the present paper we demonstrate its use for power electronics and the battery pack. In the next section, a short overview of model reduction will be given. Then in Section 3, we present a case study with a thermal runaway in a Freescale chip. In Section 4, we consider a model of an IGBT converter and in Section 5 a battery pack. Conclusion is presented in Section 6.

2 Model Order Reduction

Model reduction is an area of mathematics that in other words can be referred to as approximation of large scale dynamical system [3]. Model reduction starts after the discretization of governing partial differential equation when one obtains ordinary differential equations (1). In order to use model reduction, Eq (1) is rewritten as

$$\begin{gathered} E\dot{T} + KT = Bu \\ y = CT \end{gathered} \tag{2}$$

The difference is 1) splitting of the load vector to a product of a constant input matrix B and a vector of input functions u and 2) the introduction of the output vector y that contains some linear combinations of the state vector that are of interest in system level simulation.

Model reduction is based on an assumption that the movement of a high dimensional state vector can be well approximated by a small dimensional subspace (Fig 3 left). Provided this subspace is known the original system can be projected on it (Fig 3 right).

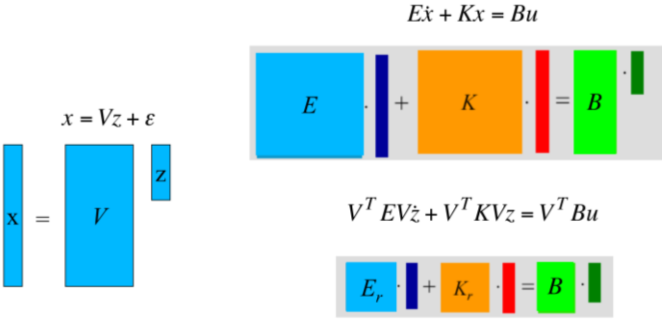


Fig. 3. Model reduction as a projection of the system onto the low-dimensional subspace

The model reduction theory is based on the approximation of the transfer function of the original dynamic system. It has been proved that in the case of Krylov subspaces the reduced system matches moments of the original system for the given expansion point. In other words, if we expand the transfer function around the expansion point, first coefficients will be exactly the same, as for the original system. Mathematically speaking this approach belongs to the Padé approximation and this also explains good approximating properties of the reduced models obtained through modern model reduction. The detailed description of the algorithm and the theorems proving moment matching properties can be found in [2][3].

The dimension of the reduced model during the model reduction process is controlled by the approximation error specified by the user. Although the model reduction methods based on the Padé approximation do not have global error estimates, in practice it is enough to employ an error indicator [4]. In our experience it is working reasonably well for a variety of finite element models.

In order to employ model reduction in practice one needs software. The software MOR for ANSYS [5][6] reads system matrices from ANSYS FULL files, runs a model reduction algorithm and then writes reduced matrices out (see Fig. 3). The process of generating FULL files in Workbench is automated through scripting. The reduced matrices can be read directly in MATLAB/Simulink, Mathematica, Python, Simplorer and other system level simulation tools. It is also possible to write them down the reduced model as a Spice model or a template for the use in VerilogA and VHDL-AMS.

3 Thermal Runaway Study with a Freescale Chip

In this Section, we briefly overview results from [7][8]. More detailed description can be found in the original publications [7][8].

Fig 4 displays the package with two power transistors (Fig 4, a) and its half-symmetry model in ANSYS Workbench (Fig 4, b). Then the chip is shown on the PCB (Fig 4, c) and thermal analysis in Workbench has been performed for this model. A typical temperature distribution is shown on the right in Fig 4, d.

MOR for ANSYS generates a reduced model in the state-space form of Eq (2) which can be directly read in Simplorer. Simplorer allows us to model thermal subsystems (Fig. 5 left) where the reduced model will be treated as a subsystem in a conservative nodal formulation: temperature and heat loss as across and through variables respectively. The reduced system also has a terminal that allows us to define the ambient temperature. The thermal impedance for one power source computed in Simplorer with the reduced model is compared with the results computed in ANSYS in Fig. 5 right. The difference is less than one percent while the reduced model has the dimension 30 (15 degrees of freedom per input) and the original ANSYS model has about 300 000 degrees of freedom. Model reduction takes only 80 s, while transient simulation ANSYS with 60 timesteps requires about 2000 s. At the same time, system level simulation in Fig 5 lasts less than a second.

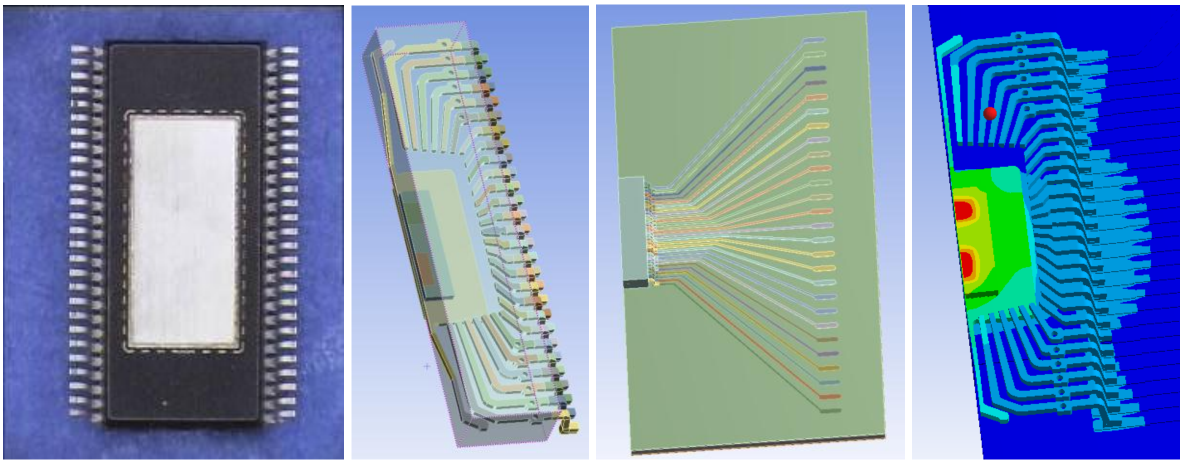


Fig. 4. a) Package with two power transistors; b) its half model in Workbench
c) the half model on a PCB d) the temperature distribution without the mold.

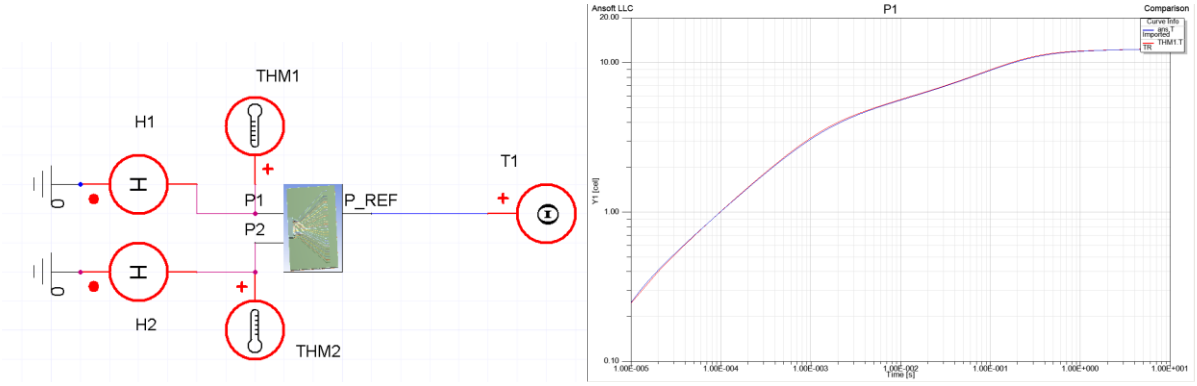


Fig. 5. Comparison of thermal impedance of one transistor in Simplorer: the reduced model vs. the original ANSYS model

Thermal runaway refers to a situation where an increase in temperature changes the conditions in a way that causes a further increase in temperature leading to a destructive result. The MOSFET transistor in the open state can be modeled as a temperature dependent thermal resistor in the electrical model. In the model shown in Fig 6 we have used only one transistor and it has been loaded sequentially with one, two or three lamps. The light-bulb model is represented using an existing Spice model which was imported directly into Simplorer. In Fig 7 the junction temperatures are shown vs. time for a different number of lumps. One can see that with three lumps the temperature for short time of about 5 ms goes over 200 degrees Celsius. The thermal model considered in this study cannot tell us whether this acceptable or not but it demonstrates us the need for transient electrothermal simulation. The stationary temperatures are acceptable for all three curves in Fig 7 and only transient simulation can reveal that the temperature goes over the critical temperature.

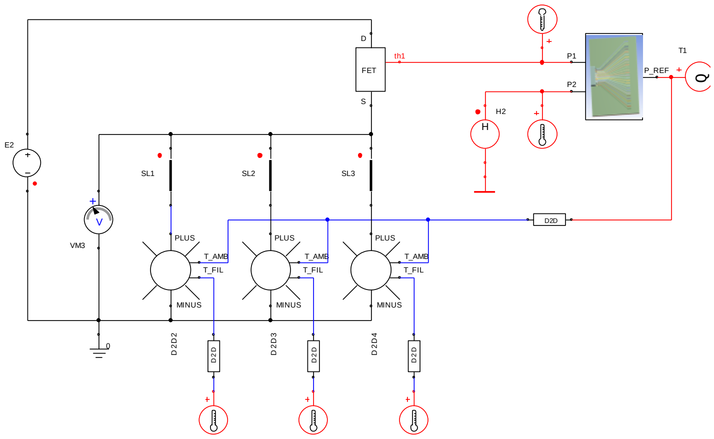


Fig. 6. Simulation model with bulb lamps

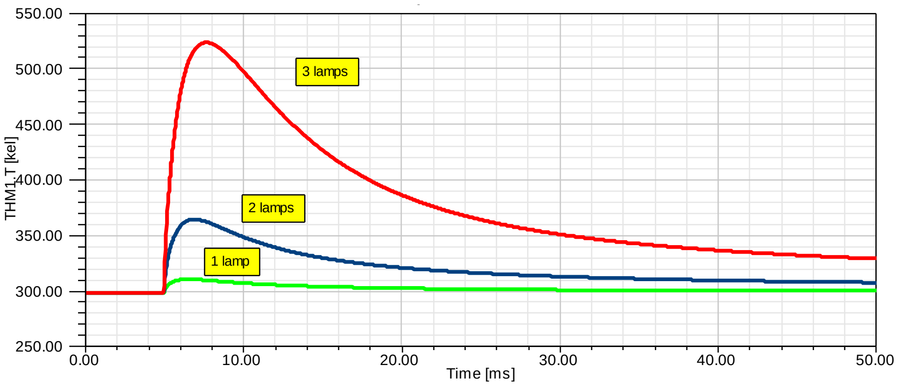


Fig. 7. Junction temperature on the transistor vs. time as a function of number of lamps

4 IGBT Converter

As a part of ECPE Tutorial [9], thermal management of an IGBT converter shown in Fig 2 has been performed with ANSYS Icepak. The model has been simplified with the assumption that the heat flow from IGBTs goes only in the direction of the heat sink, that is, the upper surfaces of IGBTs has been considered as adiabatic (see Fig. 8 left). The geometry of semiconductors as well as of the heat sink has been further simplified and the final Icepak model is shown in Fig 8 right. The typical simulation results, the temperature distribution on IGBTs and heat sink as well as flow velocities in the cross section of the model, are displayed in Fig 9.

The simulation results have been validated against experimental measurements for several stationary simulations. The results are presented in Fig 10, the difference between temperatures measured at three points within the simulation domain with simulation results being about a few degrees. The comparison for transient simulation has been also performed, the difference being also a few degrees.

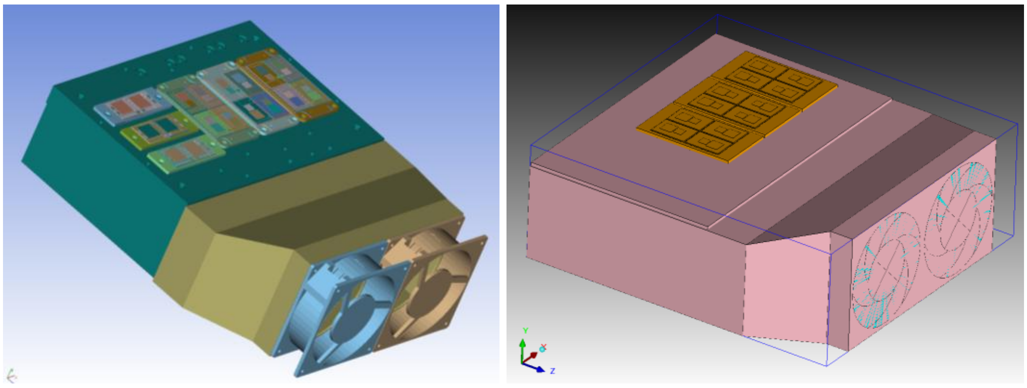


Fig. 8. The model of the IGBT converter in Icepro (left) und Icepak (right)

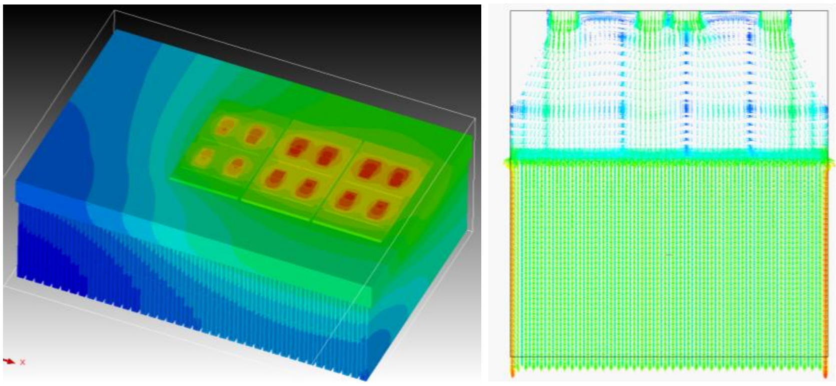
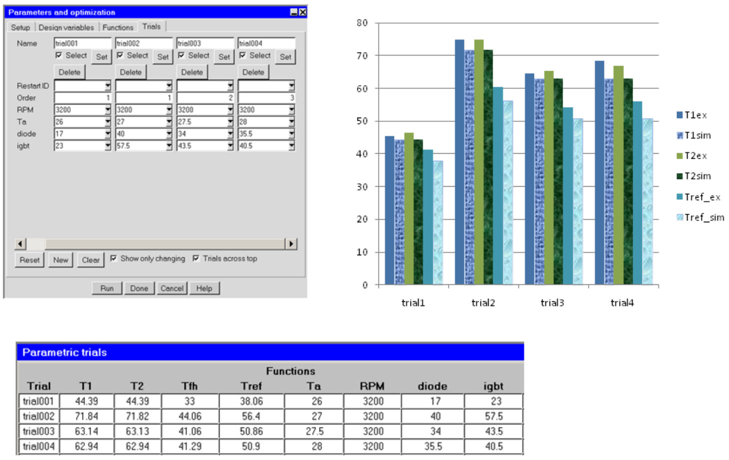


Fig. 9. Typical simulation results in Icepak



Name	trial001	trial002	trial003	trial004
	☑ Select	☑ Select	☑ Select	☑ Select
Restart ID				
Order	1	1	2	3
RPM	3200	3200	3200	3200
Ta	26	27	27.5	28
diode	17	40	34	35.5
igbt	23	57.5	43.5	40.5

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Parametric trials

				Functions				
Trial	T1	T2	Tfh	Tref	Ta	RPM	diode	igbt
trial001	44.39	44.39	33	38.06	26	3200	17	23
trial002	71.84	71.82	44.06	56.4	27	3200	40	57.5
trial003	63.14	63.13	41.06	50.86	27.5	3200	34	43.5
trial004	62.94	62.94	41.29	50.9	28	3200	35.5	40.5

Fig. 10. Comparison of Icepak simulation with experimental results

The number of inputs in this case is equal to 12 (6 IGBTs and 6 diodes), as the goal is to allow the power dissipation of all semiconductors to change independently. The number of outputs is also 12, they correspond to junction temperatures of the semiconductors. In this case, the reduced model of the dimension equal to 180 (15 degrees of freedom per input) could describe the transient response of the original model with accuracy better than 1% for wide range of different time constants (see Fig 11 where time is given in the logarithmic scale). As in the case of the Freescale chip, the time of model reduction was comparable with a few time integrations steps of the original high dimensional model while the electrochemical system simulation in Simplorer with the reduced model (see Fig 12) was about one minute.

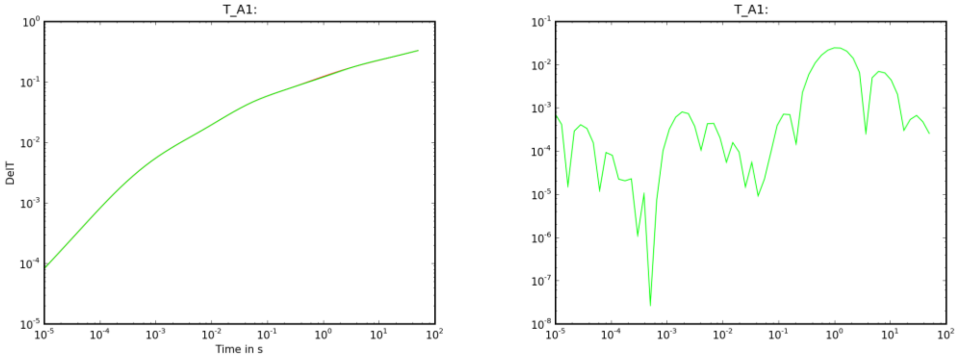

Fig. 11. Comparing the thermal impedance of the reduced model with the original model. Left is the thermal impedance, right is the relative difference between the original and reduced models.

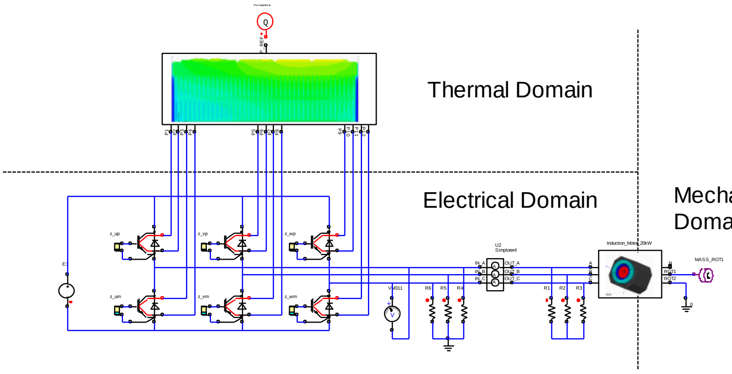

Fig. 12. Electrothermal simulation with the IGBT converter in Simplorer

5 Battery Pack

In this section the results from [10] will be presented. The finite element model of a battery pack has been developed by the company Lion Smart in ANSYS [11][12] (see Fig 13). The model consists from 32 individual batteries that have been cooled through pipes modeled by means of one dimensional FLUID116 elements in ANSYS. The finite element model has the dimension roughly 50 000 degrees of freedom and its transient simulation for 100 timesteps takes 40 min.

MOR for ANSYS has been employed to reduce the ANSYS model. Again the reduced model with 15 degrees of freedom per input was able to approximate the original model with accuracy better than 1% (see Fig. 14). Transient simulation of the reduced model takes less than one second.

The coupling of the reduced model with the impedance model of one battery cell is shown in Fig 15. The battery generates power dissipation that is fed to the compact thermal model and at the same time battery parameters depends on temperature that comes from the thermal model. It is also possible to model each battery cell independently. To this end one has to couple more electrical models with the thermal model.

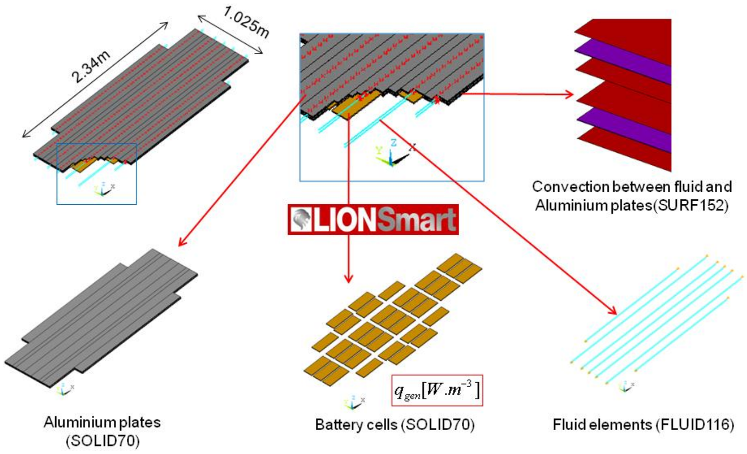

Fig. 13. The battery pack model (http://www.lionsmart.de/)

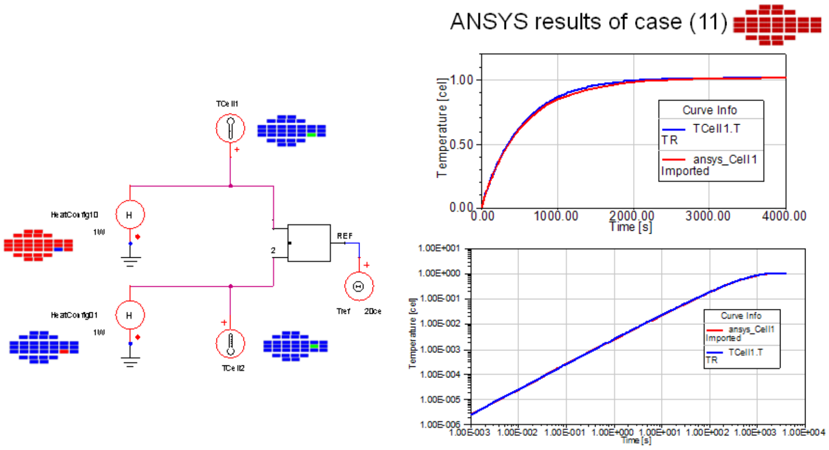

Fig. 14. The comparison in Simplorer of the thermal impedance for one load case

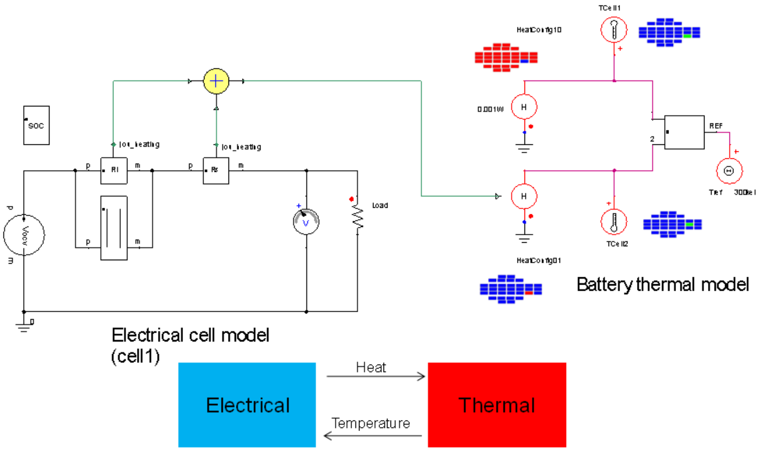

Fig. 15. Electrothermal simulation of one cell in Simplorer

6 Conclusion

We have shown that model reduction is an efficient tool automatically to generate an accurate compact thermal model with multiple inputs. The advantages of the method are as follows:

- The method uses the system matrices from the finite element model directly.
- The method is automatic. The user should check once the dimension of the reduced model. In our experience the accuracy of one percent is achieved with 10-15 degrees of freedom in the reduced model per input.
- The model reduction process is fast. The time for model reduction is comparable with that of a static solution and much smaller than a single transient run with the original finite element model.
- The nonlinearity in the input function (temperature dependent power dissipation) is completely preserved as the input function does not take part in the model reduction process.

Finally we would like to mention that the new development allows us to preserve the film coefficient and the mass flow as parameters directly in the reduced model [13][14][15]. This allows us to model at system level the thermal behavior of a battery pack when the mass flow changes, see Fig. 16.

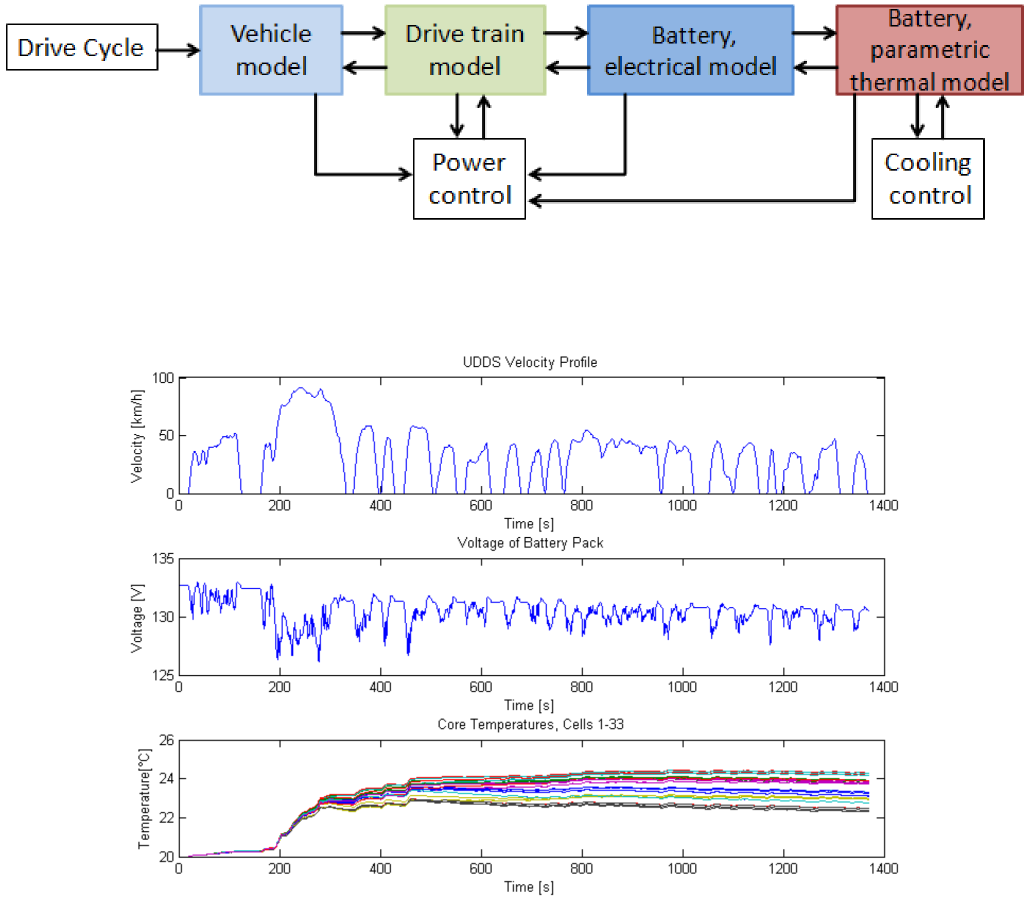

Fig. 16. Top: a block scheme of system level simulation with a parameterized reduced model, bottom: simulation results (Courtesy of Michael Geppert, Lion Smart [11][15])

7 References

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