Model Reduction for Power Electronics Systems with Multiple Heat Sources

A. Augustin*, T. Hauck*, B. Maj§, J. Czernohorsky§, E.B. Rudnyi‡ and J.G. Korvink‡
*Freescale Semiconductor, Schatzbogen 7, D-81829 Munich, Germany
§Continental Automotive Systems AG, P.O. Box 90 01 20, D-60441 Frankfurt, Germany
‡IMTEK, Laboratory for Simulation, University of Freiburg, Georges-Koehler-Allee 103, D-79110 Freiburg, Germany
Email: adam.augustin@freescale.com, bartosz.maj@contiautomotive.com, korvink@imtek.de

***Abstract*— The paper demonstrates the model order reduction procedures applied to semiconductor devices with multiple heat sources. The approach is demonstrated for a device with nine heat sources where some of them are permanently active and other work under switching conditions. For the order reduction the software package *MOR for ANSYS* is used, which is based on the Krylov subspace method via the Arnoldi algorithm.**

I. Introduction

Modern semiconductor technologies allow the development of power electronics systems with manifold functionality integrated on one single die. Due to this everlasting process, the devices include more and more heat sources, which have to be considered in thermal simulations. For complex package and heat source configurations as well as for different applications, accurate thermal models are needed.

As module configuration is close to a multilayered block structure, one of the simulation approaches is based on an analytical solution of the heat transfer equation [1]–[3]. Obviously, real geometry is different from the idealized geometry required by the analytical solution and the finite element method seems to be the only valid alternative for detailed thermal simulations in the general case (see for example [4]). Unfortunately, the biggest disadvantage of this approach is high simulation time because of high dimensional models with hundreds thousands degrees of freedom. One possible way to overcome this problem is to use mathematical methods in order to reduce the system order with a minimum loss of accuracy.

A formal model reduction approach [5] (overview from engineering viewpoint in [6]) allows us to take a high dimensional finite element model and generate its low-dimensional approximation. As such, it is an ideal candidate for the goal above. Several research groups have already documented its successful application to a thermal problem [7]–[10].

However, the formal model reduction approach also puts some limits for the original thermal problem. For example, it happens that its application is not straightforward for cooling of electronic components as considered by the DELPHI and PROFIT consortium [11]–[14]. The main reason is that the use of film coefficients is limited for forced convection within a volume with complex geometrical constraints. In this case, one cannot avoid a joint thermal-CFD simulation and compact thermal models should possess special properties.

In our case, the situation is different. 85 % of heat is removed by conduction and there is no forced convection. The remaining 15 % of heat is removed by natural convection. Additionally, film coefficients have been validated by means of experimental monitoring of temperature. As a result, formal model reduction can be employed for the thermal problem without any further modification. Finally, we should stress that dynamic behavior must be preserved in our case.

The structure of this paper is as follows. In section II a short introduction into the model order reduction theory will be presented together with the reduction process for devices with multiple heat sources. In section III the necessary preparatory steps for calculations with reduced models will be explained including the consideration of some permanent active heat sources. In section IV the presented simulation results will be discussed. Finally, in section V some concluding remarks will be made.

II. Model Reduction Process

Using the finite element simulation software ANSYS, a geometrical and physical model is generated. The model should concern all thermally relevant components to represent the real device as good as possible.

A. General Theory

After the discretization, the finite element model is expressed as follows:

$$\begin{aligned} \mathsf{E}\frac{dT(t)}{dt} + \mathsf{K}\,T(t) &= \mathsf{B}\,u(t) \\ y(t) &= \mathsf{C}\,T(t) \end{aligned} \qquad (1)$$

where $y(t)$ is the vector of unknown temperatures at the nodes, and $T(t)$ is the state vector. E and K are the heat capacity and heat conductivity system matrices, B is the input matrix, and C is the output matrix. The vector $u(t)$ comprises n input functions for the n heat sources. The output matrix specifies particular linear combinations of temperatures which are of interest to an engineer. The system matrices as well as the load vectors have been read from ANSYS binary `*.full` and `*.emat` files. Model reduction is performed in the Laplace domain, that is, for the transfer function of eq. (1)

$$H(s) = \mathsf{C}\,(s\mathsf{E} + \mathsf{K})^{-1}\,\mathsf{B} \tag{2}$$

and it is based on an assumption that there exists a low-dimensional subspace V that accurately enough captures the dynamics of the state vector $T(t)$

$$T(t) = \mathsf{V}z(t)\,. \tag{3}$$

Obviously, $z(t)$ indicates here the state vector of the reduced system. To generate the low-dimensional subspace V we expand eq. (2) around the Laplace variable $s_0 = 0$ and then we use implicit moment matching via the Krylov subspace method. Finally, for the reduced system we obtain

$$\begin{aligned} \mathsf{V}^\mathsf{T}\mathsf{E}\,\mathsf{V}\,\frac{dz(t)}{dt} + \mathsf{V}^\mathsf{T}\mathsf{K}\,\mathsf{V}\,z(t) &= \mathsf{V}^\mathsf{T}\mathsf{B}\,u(t) \\ y(t) &= \mathsf{C}\,\mathsf{V}\,z(t)\,. \end{aligned} \tag{4}$$

B. Reduction Process for Multiple Heat Sources

In order to generate the reduced model with multiple heat source devices the right strategy has to be chosen. For example, for applications under switching conditions in kHz range, model generation for each particular switching event is not practicable, since for the description of only few second response, hundreds of load steps are needed. Fortunately, the input function in eq. (1) does not take part during model reduction process and can be passed to the reduced model in eq. (4) without changes. This means that provided we have split the load to the product of B and u, for each particular heat source only one load step has to be generated. Switching conditions can be implemented afterwards by applying pulsed input functions to the reduced model. This procedure allows a very comfortable control on the input function characteristics without any additional model order reduction runs.

As a demonstration, we have chosen a device with nine heat sources. In Fig. 1 the finite element model of the investigated device is shown. Since the printed circuit board with the heat sink is much bigger than the package only the much more interesting section around the investigated devices (together with the package) is shown. The device is assembled in a package with an exposed lead frame. This allows a direct connection between the package and the heat sink, which is protruded from the bottom side to the top surface of the board. Fig. 2 indicates schematically the die in a top view with all nine investigated heat sources. Five of them are permanently active, the other four sources are dynamically switched on and off. In principle, only five load steps could be generated, as all the permanent sources could be joined with each other. However, we have generated nine separate load steps for each heat source to

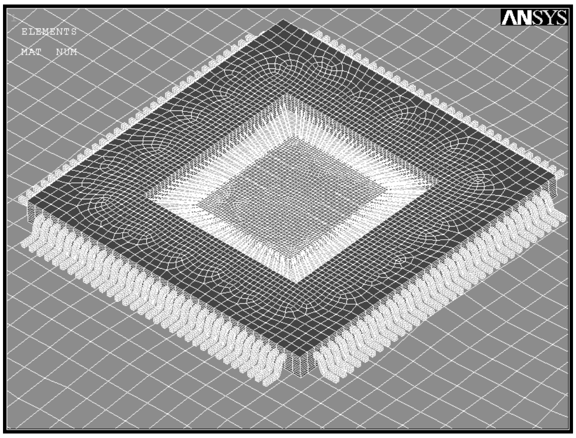

Fig. 1. ANSYS model of a power device placed on PCB with a heat sink. To have a view on the die, the enclosing mold compound has been removed

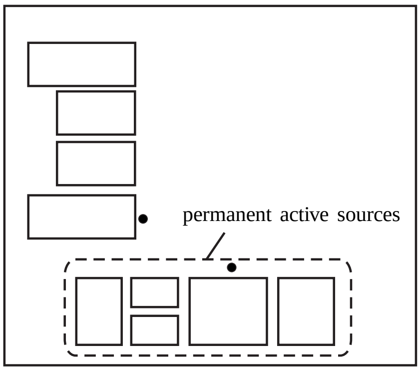

Fig. 2. Schematical top view of the die. Five heat sources are permanent active. The other four heat sources work under switching conditions. The dots indicate the positions of two build-in sensors which are used for model verification and result presentation

allow the change in the amount of power dissipation within the five permanent active heat sources individually.

If the power dissipation is set to 1 W during the load generation, the effective power dissipation in the reduced model can be controlled by the amplitude of the input function. Obviously, using this method the input functions for five heat sources are constant functions $f_i(t) = P_i$ with $i = 1, \ldots, 5$ and the effectively dissipated power P_i. The input functions for the dynamic heat sources are pulse functions as shown schematically in Fig. 3 with $f_j(t) = P_j \cdot f_{pulse,j}(t)$, $j = 6, \ldots, 9$ and the amplitudes P_j. In order to draw a distinction between the input functions $f_{pulse,j}(t)$ in Fig. 3 both functions are scaled. Finally, the input matrix B is a $m \times 9$ matrix, with m as the order of the reduced model.

Because of the special operation mode of *MOR for ANSYS* [16] all boundary conditions are taken from the first load step file, therefore these conditions must be set only for the first load step besides the definition of power dissipation for the first

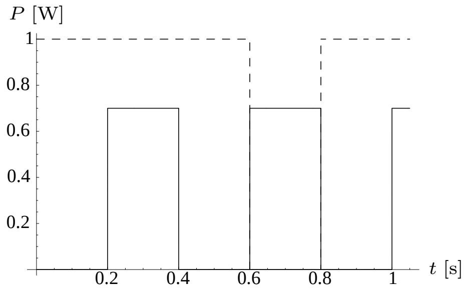

Fig. 3. Schematical view of the input functions for transient simulations. Two heat sources are using the function (solid) with 0.4 s period and the other two use the 0.8 s period function (dashed). The amplitudes are adjusted later to appropriate values

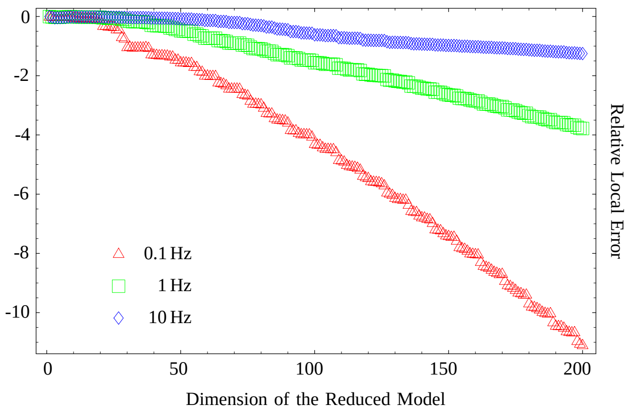

Fig. 4. Local error estimation for the reduced model depending on the frequency and model order

heat source. For the remaining eight load steps, only a particular source (two until nine) was active in each load generation step. Finally, nine load step files are created by ANSYS: `file1.full` (convection and only source one is on with $P = 1\,\mathrm{W}$), `file2.full` (only source two is on with $P = 1\,\mathrm{W}$), `file3.full` (only source three is on with $P = 1\,\mathrm{W}$), and so on until nine. As was mentioned before, the dynamic state of the four transient heat sources will be implemented later, simply by the use of the pulsed input function as shown in Fig. 3. In order to begin the reduction process all output positions (nodes in the finite element model) must be set, for which the temperature will be monitored, as well. Using all generated files and the information about the outputs, the reduction process can be performed with *MOR for ANSYS*.

III. Preparatory Steps

At the beginning of the simulation process, on one hand, the decision about the order of the reduced model must be made as well as, on the other hand, the heat generation of the permanent heat sources must be considered.

A. Model Order Estimation

Implicit moment matching does not have global error estimates. In order to determine the dimension of the reduced model, we suggest to use a local error estimate at some frequency that is roughly inversely proportional to the rise time. Fig. 4 displays logarithm of the relative error for three frequencies, 0.1 Hz, 1 Hz and 10 Hz. We define the relative error as

$$\left| \frac{H_{full}(f) - H_{red}(f)}{H_{full}(f)} \right| \tag{5}$$

with H as transfer functions of the reduced and full system.

As the expansion point was zero, then the higher the frequency the slower the convergence. The error of 1 % can be approximated by first fifty generalized states at 0.1 Hz. At 1 Hz the error of 1 % can be reached at the dimension of 100, first. Based on these results, we chose the order of the reduced model as 100. For this dimension, we can keep the accuracy form zero up to 1 Hz within 1 % using the expansion point $s_0 = 0$ for the model reduction process, what is enough for the application in question.

B. Consideration of Permanent Heat Sources

To perform transient calculations with permanent heat sources one have to shift the pulse inputs (necessary for the dynamic sources) by a sufficient time in order to reach the steady state caused by all permanent sources as shown in Fig. 5. As soon as this state is reached, the pulsed heat sources can be activated. In terms of simplicity, we start here with 2000 s to make sure that the steady state is reached. In reality the steady state is reached much faster.

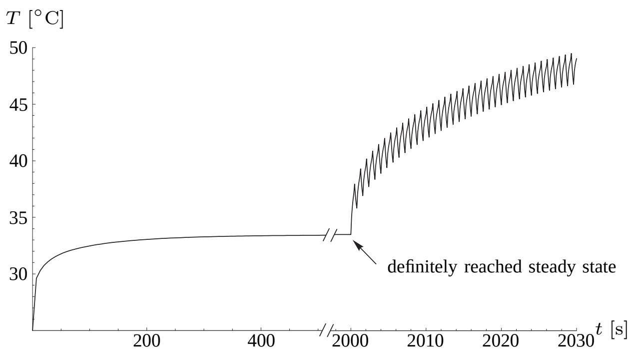

Fig. 5. Temperature rise on one output showing the consideration of the permanent active heat sources. To be certain for a steady state and in terms of simplicity, all pulse functions for the dynamic heat sources are shifted by 2000 s

C. Model Verification by Measurements

Since the investigated device contains several build-in temperature sensors distributed over the entire die surface, we have used seven of them to verify the finite element model. First, all sensors have been calibrated separately. Using this calibration approach we estimated an accuracy of 3 % for the steady state. Using the calibrated model, transient measurements and simulations with the reduced model were done.

IV. Results

First, we show here the improvements in time consumption using the reduced model for transient simulations. In ANSYS for a transient simulation with 15 s duration time and a pulse period of 0.4 s, at least 38 load steps are needed. Therefore, transient simulation with very bad accuracy due to high numerical errors during integration in time needs at least 874 s of runtime. The entire calculation with the reduced model, including the model reduction process and a time vector with 4100 time steps, needs 158 s of runtime, from which 150 s take for the model reduction and 8 s for transient integration. Note that integration of the full model (with 104346 nodes) in ANSYS for 4100 time steps would take about 26 hours.

For the presentation of the results we chose two sensors/outputs. As can be seen in Fig. 2 one build-in sensor is placed near the permanent active heat source and the other in the vicinity of a dynamic source. In Fig. 6 the results for these two sensors/outputs are shown. Solid lines show the simulation results, dots and the dashed line show the equivalent measurements. The output curve of the left

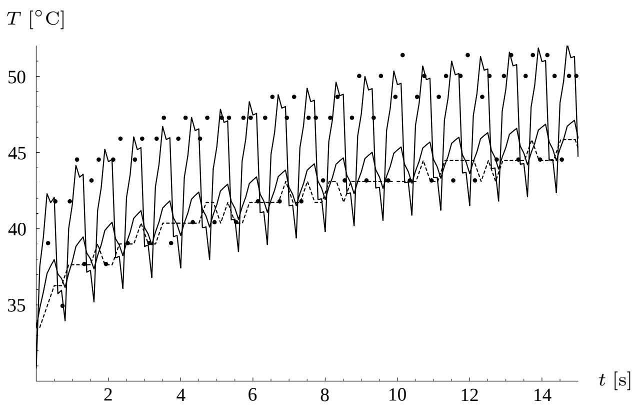

Fig. 6. Temperature rise caused by four dynamic heat source with two different input functions as well as by five permanent active sources at $T_{amb} = 25\,^\circ\mathrm{C}$. Solid lines indicate the simulation results of the reduced model with order 100. Dots (left sensor in Fig. 2) and the dashed line show transient thermal measurements. Time scale is shifted to the begin of the pulsed input functions

sensor shows very high gradients, caused by the vicinity to the dynamic heat sources. The measurements at this sensor are indicated by dots. Since the distance of the other sensor to the dynamic sources is much larger, the gradients here are much lower. On both solid curves, the switching times of the particular sources can be seen very good. However, the left sensor shows these switching activities much more pronounced. The measurements (dots and dashed line) show a small difference that can be explained by both measurement errors and approximations made during the finite element modeling of the original high dimensional model. Nevertheless, a very good correlation with the simulated results can be observed.

V. Conclusions

In this paper, we have shown the application of the model order reduction method for a power device with multiple heat sources. The treatment of two different heat sources (permanently active and dynamic sources) was explained. Using complex measurements, the temperature was monitored with several build-in temperature sensors on the die, in order to verify the finite element model. All simulation results, for steady state and transient conditions, show very good correlations with measurements.

Depending on the frequency of input functions, the order of the reduced model can be reduced down to 100. However, for faster switching conditions multiple expansion points should be used, in order to keep the dimension of the reduced model applicable.

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