

Integrated Coupled Simulation Of The Whole Thermal Path

Today simulations are indispensable when developing complex electronic applications. So far thermal, mechanical and electrical impacts have been considered almost independently from each other. This has led to failures and wrong prognosis as well as exaggerated dimensioning. A comprehensive approach considers the interactions between the different disciplines and optimally reflects the mechanics, electrics and fluid dynamics at the same time. This results in a much better reliability of the system prognosis.

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Circuits and elements used in power electronics are subject to boosting demands. Power density of components is steadily increasing. They are operated close to their limits, thus augmenting the risk of thermally caused outages. In order to describe the system as a whole, mechanic-thermal-electrical interactions have to be taken into consideration.

So far, these three disciplines have been contemplated primarily independently from each other. Just to give an example, computational fluid dynamics (CFD) simulations serve to analyse the thermal balance as a stand-alone technique, while the effects of heat conductivity and radiation can be shown. This is an established method which allows a reasonable prognosis of thermal processes and fluid dynamics based on more or less constant parameters, such as mass flow rate or dissipative power losses.

On the other side, electronic circuit simulations are well anchored and necessary when developing complex circuits. All influences and parameters describing the system behaviour can be specified by computer simulation. Thermal-mechanic impacts, however, are mostly approximated by worst case assumptions but not actively taken into account or even suppressed.

All in all, the following questions remain unanswered: The non-linear behaviour of power semiconductors relating to dissipative power while working within critical operating ranges; mechanical impacts due to thermally caused structural deformations, hence changed geometries and gaps, resulting in decoupling the thermal path; non-linear behaviour of thermal resistances and capacities; pressure dependencies and volume expansion factors having direct impact on the thermal path, virtual modelling and

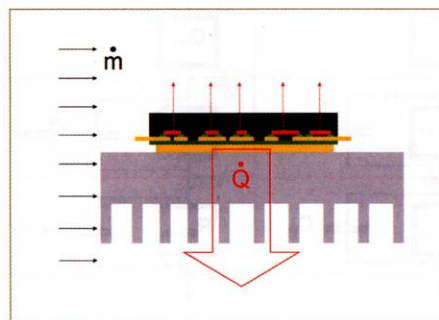


Figure 1: Thermal path of the whole system

implementation of thermal interface materials into the total system; and distinguishing robust from non-robust sensitive systems and their respective interactions.

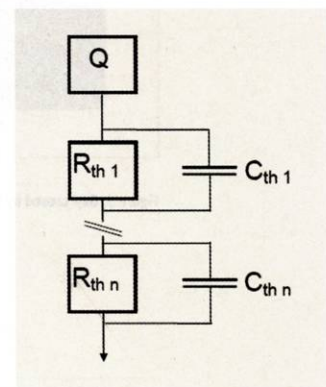
Established software as technical platforms for Finite Element Analysis (FEA) for simulating thermal-mechanical interactions and couplings have been present on the market for a long time. They serve to entirely analyse mechanical and thermal physics, being coupled with the relevant feedback effects to the system. Coupling an electronic circuit simulator, however, has not entered the market so far.

The virtual development requires to gain a comprehensive mechatronic understanding and a deep insight into the main processes. All significant disciplines need to be supported by adequate tools and be meshed from the scratch of a development project when being employed.

Thermal-mechanical interactions

Power reduction e.g. by frequency drops have been a regular means to mitigate thermal impacts when operating at the borderline of critical load limits. This is a well known measure but still remains an auxiliary counteraction only. Optimising the

Figure 2: The thermal path



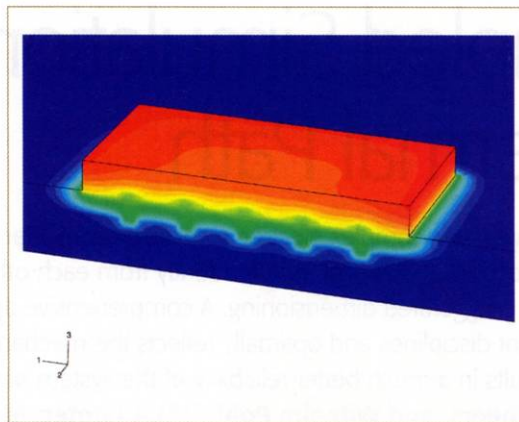


Figure 3: 3D thermal path with calculated temperature area

constants are considered according to Figure 2.

The thermal resistance R_{th} and the thermal capacity C_{th} mainly depend on the contact area and pressure, material thickness, thermal conductivity, density, specific heat capacity and volume.

All these parameters are highly non-linear. Worst case scenarios assuming constants or merely linear dependencies are misleading and lead to wrong design and dimensioning, thus having crucial long-term economic impacts. The developer takes the risk that the worst case presumed does indeed not reflect the extreme situation. This is also true for thermal interface materials being used as significant thermal joints. Figure 3 virtually shows how heat is conducted through a thermally conductive gap filler put under a through-hole via board.

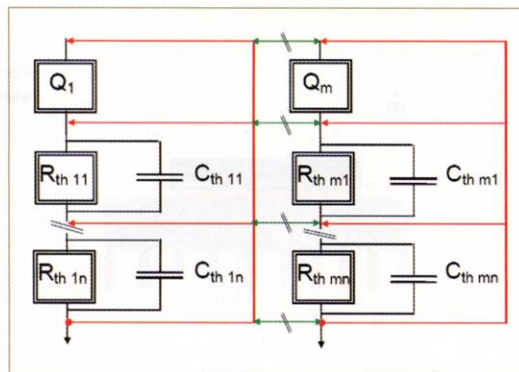


Figure 4: Thermal path as closed loop with feedback

A multi-dimensional analysis of the whole electrical-mechanical system from the semiconductor to the heatsink and ambience including material properties is therefore required. This results in a closed loop non-linear system strongly determined by thermo-mechanical feedback (Figure 4). To describe the mechatronical behaviour the following effects have striking impact: non-linear thermal and mechanical material properties comprising Young-Modulus, volume expansion coefficients, thermal conductivities, material densities; horizontal thermal coupling of separated electronic and peripheral elements on the board and anisotropic thermal conductivity; interactions of elements within the thermal path by vertical thermal conductivity; effects caused by n-dimensional feedbacks e.g. through mounting pressure, thermal

overall efficiency of the mechatronic system is the better way (Figure 1).

CFD simulation of dynamic currents (air, water), radiation into ambience or heat conduction to close peripheral sinks is well-known and can be solved by standard tools. It will not be further discussed here. The conventional design by simulation

does not foresee to consider either non-linear or feedback of each step within the thermal path. These interacting effects have only been partially taken into account. The system has been reduced to one dimension or widened up to two dimensions when transient processes caused by capacities and resulting time

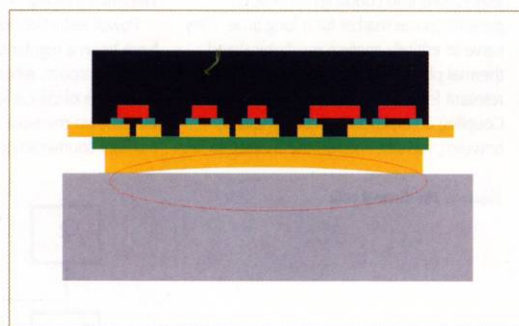


Figure 5: Gap caused by thermally induced deformation

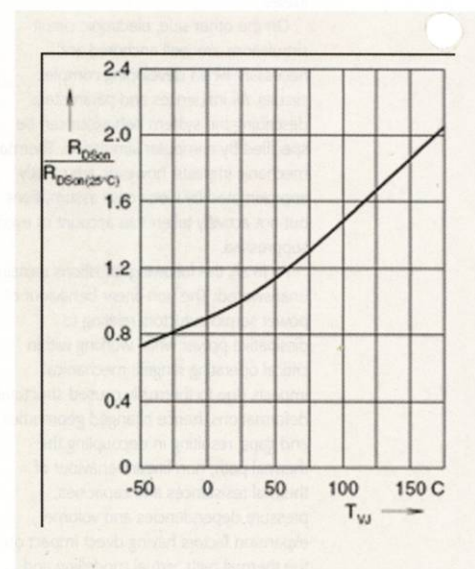


Figure 6: Temperatur caused increase of resistance

Figure 7: Coupled mechatronical simulation

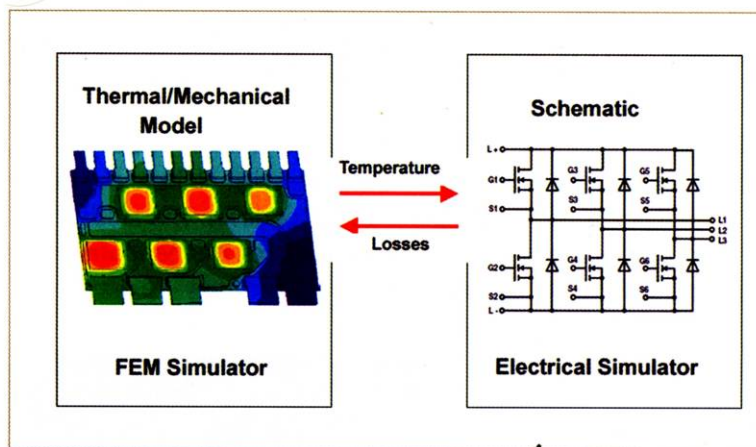
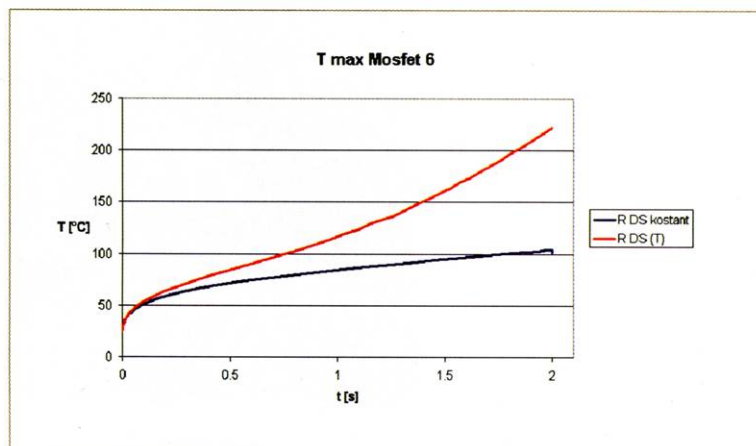


Figure 8: FET temperature with (red) and without (blue) feedback



expansion, and leading to deformations and possible gaps (see Figure 5) as well as impacts on sensitive subsystems.

A comprehensive understanding of the whole system and above all the thermal part is indispensable in order to model the thermo-mechatronic close to the reality. Assuming induction of realistic dissipative power (for circuit simulation) and heat dissipation (for CFD simulation) allows the entire and substantial virtual description of the thermal path as a system.

Circuit simulation with dissipative power feedback

Every electronic part shows temperature dependencies and changing properties independently on the respective type at heat-up (Figure 6) with immediate impact on the thermo-mechanical and electrical steady state behaviour. Thus temperature ideally serves as underlying coupling parameter for further system analysis comprising the dissipative power as function of temperature, while connecting electronics to mechanics.

The thermal and dissipative feedbacks

affect changing operational points of electronic elements such as at MOSFETS, which are then considered in the circuit simulator.

Semiconductor dissipative behaviour and efficiencies, as well as dynamics, are sensitively influenced and therefore have a significant impact on the whole system. This approach leads to closed loop interactions with temperature and dissipative power being the main factors. Operating in critical ranges that have not been verified, neither by test, nor by prototypes reflecting reality implies the risk of gradually leading to instability. This results in short- and/or long-term outages as well as cancer-like loss of reliability.

All these interactions have successfully been analysed, using realistic examples with coupled mechatronical simulation. Given the worst case, a non-stable thermal system could be proved (Figure 7) with prognosis of later outages of one single or multiple semiconductors. The introduced closed loop approach is ideal to be applied for power modules with Direct Copper Bond (DCB) or Active Metal Plate (AMP)

substrates, circuits on FR4 boards thermally linked by vias and interfacing gap-fillers, Insulated Metal Substrate (IMS) thick copper board technologies. The outcome of calculations proves that the entirely coupled analysis describes mechanical-electronical-thermal dependencies on temperature and dissipation. The electronic circuit simulator is coupled with the FE-simulator by a central control software. A FET temperature simulation with (red) and without (blue) feedback is shown in Figure 8.

Conclusions

There are plenty of tools available on the market for simulating mechanics, electronics, fluid dynamics and thermal processes. Coupling all the disciplines that have been contemplated mostly separated from each other so far has been realised by trespassing the specific limits of each tool when designing power electronic systems. Interactions of different parameters are taken into full account resulting in a closed loop system. This leads to a better understanding and a reliable prognosis of the system behaviour.