Total Thermal Management: Using Coupled Simulation

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Today simulations are indispensable when developing complex electronic applications. Up until now, thermal, mechanical and electronic factors have been considered almost independently from each other. This has led to false prognosis and excessive dimensioning, as well as outages.

A comprehensive simulation approach considers the interactions between the different physical disciplines and optimally reproduces thermodynamics, mechanics, electronics and also fluid dynamics at the same time. All in all, this results in a much better reliability of the system prognosis.

Circuits and elements used in power electronics are subject to growing demands. They are operated close to their threshold values, thus augmenting the risk of thermally caused outages. In order to describe the system as a whole, mechanical-thermal-electrical interactions have to be taken into thorough consideration. So far, these three disciplines have been considered primarily independently from each other. CFD and electronic-circuit simulations are state-of-the art and necessary when developing complex circuits and doing computational fluid-dynamics analysis. Thermal-mechanic impacts, however, are mostly approximated by rudimentary worst-case assumptions but not actively taken into account, or they are even ignored.

The following questions remain unanswered: How deal with the non-linear behaviour of power semiconductors? What is to be done about the mechanical impacts due to thermally caused structural deformations, resulting in changed geometries and gaps (Figure 1)? What will be the effect the non-linear behaviour of thermal resistances and capacities? What will be the effect of the pressure dependencies and volume expansion? How distinguish robust from non-robust sytems and their respective interactions?

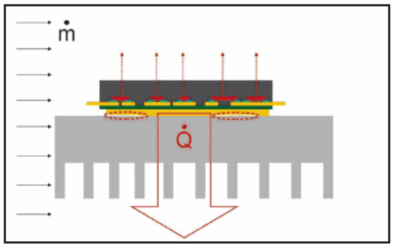

Figure 1: A thermal gap caused by thermally induced deformations.

⇨Thermal-mechanical interactions

Power reduction has been a regular means of mitigating thermal impacts when operating at the borderline of critical load limits. This is a well-known but inefficient auxiliary counteraction. Optimising the overall efficiency of the mechatronic system offers a much more effective path to maximum system performance. The thermal resistance R_{th} and the thermal capacity C_{th} depend mainly on the contact area, pressure, material thickness, thermal conductivity, density, specific heat capacity and volume. All these parameters are highly non-linear. Worst-case scenarios, assuming constant parameters or merely linear dependencies, can often be rather misleading and may result in faulty design and dimensioning. This can have crucial long-term economic impacts on the system design: the developer takes the risk that the worst-case scenario presumed does not actually reflect reality.

Therefore, a multi-dimensional analysis of the entire electrical-mechanical system, from the semiconductor to the heat sink, is required. This results in an n-dimensional closed-loop non-linear system strongly influenced by thermo-mechanic feedback.

In describing the mechatronic behaviour the following effects are major factors: non-linear thermal and mechanical material properties comprising Young-Modulus, volume expansion coefficients, thermal conductivities and material densities; horizontal thermal coupling of separated electronic and peripherial elements on the board through anisotropic thermal conductivities; interactions of elements within the thermal path due to vertical conduction; effects caused by n-dimensional feedbacks, for example through mounting pressure, thermal expansion, and deformations leading to possible gaps; and repercussions on sensitive subsystems.

⇨Circuit simulation with feedback

Regardless of its mechanical form, the thermal characteristics of the components used to make up a system must be considered in detail. All electronic components show temperature dependencies with changing properties as they heat up (Figure 2), resulting in an immediate impact on their thermo-mechanical and electrical steady-state behaviour. Thus, temperature ideally serves as an underlying coupling parameter that will allow further system analysis, containing dissipative power as a function of temperature while connecting electronics to mechanics.

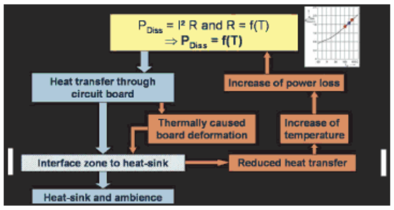

Figure 2: A closed-loop system with changing operating points.

Thermal and dissipative feedback factors modify the operating levels of electronic components - such as power MOSFETS - that are calculated and implemented in the circuit simulator.

This approach leads to closed-loop interactions with temperature and dissipative power being the main factors, as shown in Figure 2 with $PD_{iss} = f(T)$. Operating a system in critical ranges that have not been verified, either by numerous operational testing or by a number of (expensive) prototypes, means running the risk of evental instability. This results in short- and/or long-term outages as well as cancer-like loss of reliability. Moreover, all these practical measures do not necessarily lead to a comprehensive and deep understanding of the total system behaviour. Figure 3 shows geometry deformations of a metal-substrate board caused by the discussed mechatronic impacts as well as the dynamic temperature distribution caused by a changing steady-state of cooling with complete signal feedback at load and without feedback.

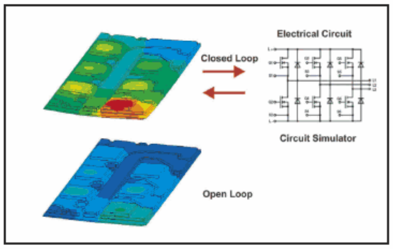

Figure 3: Thermally induced deformations of a metal-substrate board at load with and without signal feedback.

The closed-loop approach that has been discussed here is suitable for applying to IMS (insulated metal substrate), power modules with DCB (direct-copper-bond) substrates, AMPs (active metal plates) and printed circuits on FR4 boards, all thermally linked by vias and interfacing gap-fillers. By this method, all of the various physical factors of mechanical, thermodynamic, electronic and fluid dynamics can be meshed into a network leading to an in-depth understanding of the complete system. It also helps achieve a successful design-in and configuration of the right thermally conductive interface material.

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