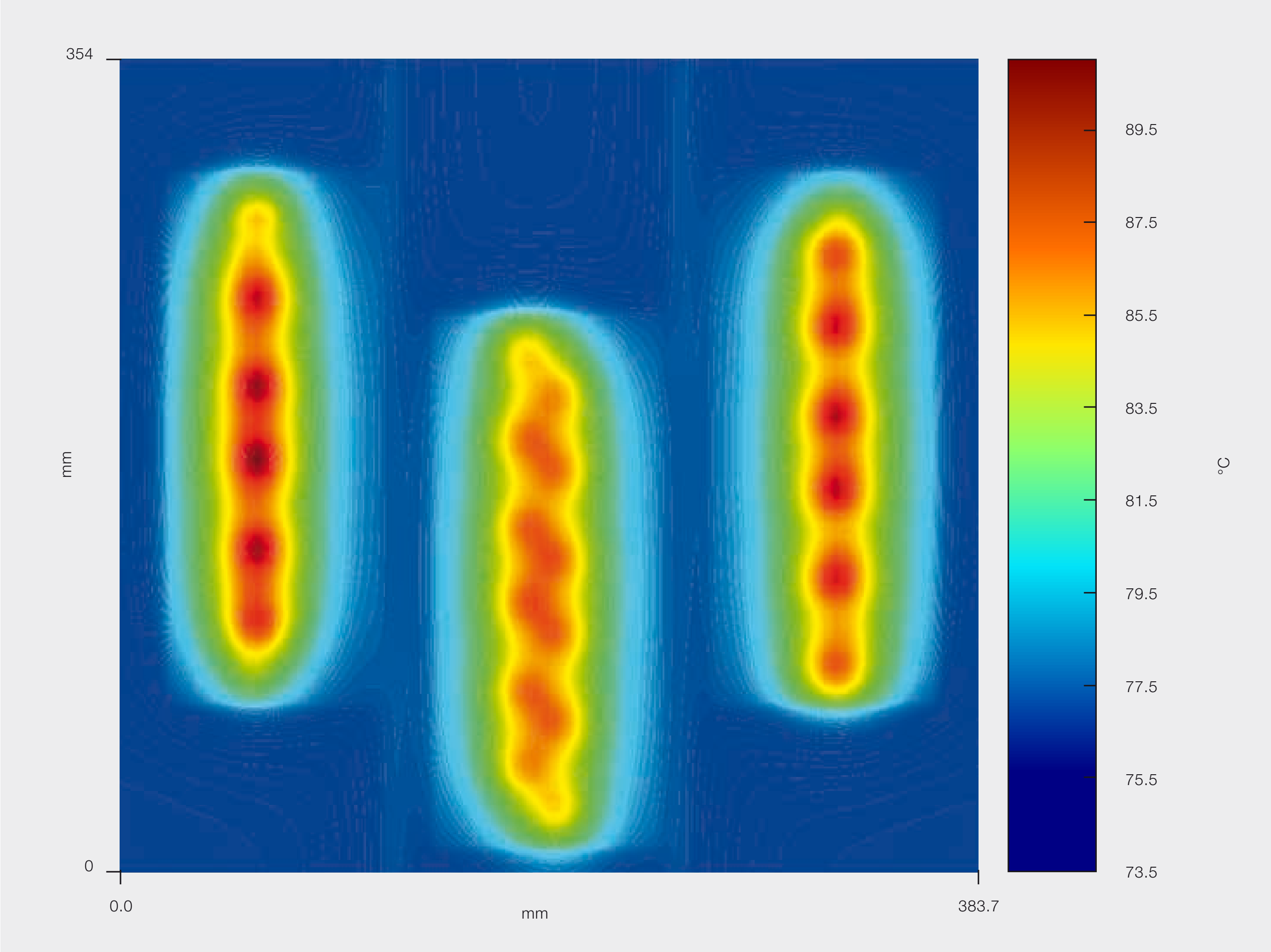


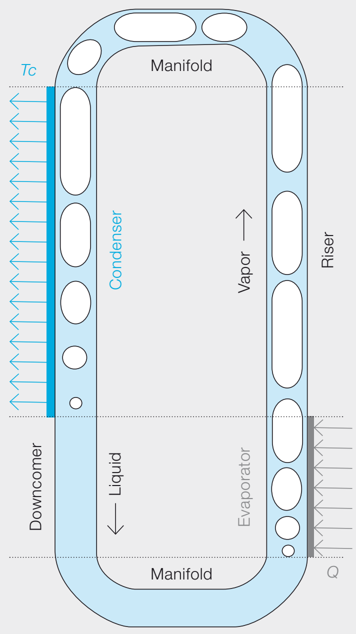
Integrated ingenuity

New simulation algorithms for cost-effective design of highly integrated and reliable power electronic frequency converters

DIDIER COTTET, BRUNO AGOSTINI, STANISLAV SKIBIN, GERNOT RIEDEL, PAWEL WOJCIK – Many readers may perceive power electronics engineering to be chiefly about circuit topologies and algorithms. Whereas these aspects continue to be vital, designers are increasingly also addressing challenges in other areas. The growing significance of integration has raised the profile of domains such as cooling, interconnects and voltage insulation and is bringing about improvements in power density, electromagnetic compatibility (EMC), and reliability. With the rising complexity of these technologies, optimal designs are no longer possible without recourse to state-of-the-art simulations.

Newly developed semiconductor devices permit faster switching at lower losses and operation at higher temperatures, while also raising fresh challenges in terms of integra-tion.

1 Two-phase thermosyphon principle



$$\frac{dp}{dT} = \frac{L}{T\,(\Delta V)}$$

Power electronics is one of the principle enabling technologies in domains such as renewable power generation, efficient power usage in industrial automation, control of power flow in smart grids, and low-loss power transmission and distribution using DC technologies. The relevant performance measures for converters in these applications are conversion efficiency, control dynamics, reliability (or availability), power density and cost.

Differentiating aspects with regard to converter design lie in the choice of integration technologies, for example enclosure materials, cooling methods, interconnections and electrical insulation. The design challenges in integration are:
- Thermal losses
- High-current conduction
- High-voltage insulation
- Electromagnetic noise
- Electro-thermo-mechanical stress

Simulations are now a state-of-the-art component of development processes in these domains. Three-dimensional (3-D) finite element analysis (FEA) of power semiconductors helps optimize the manufacturing processes and switching characteristics. At system-level, the current control schemes and the process control algorithms are simulated using circuit simulators, often combined with multi-objective optimization methods.

Recent years have seen significant advances in the domain of wide band gap (WBG) power semiconductors, bringing first silicon-carbide (SiC) and then gallium-nitride (GaN) devices to the market. These new devices permit faster switching at lower losses and operation at higher temperatures. While this delivers many benefits in terms of energy efficiency, power density and new applications, it also raises fresh challenges in terms of integration. This article looks at three integration areas where new simulation methodologies had to be developed:
- Two-phase cooling for high power density and high reliability
- Design for electromagnetic compatibility (EMC)
- Electro-thermal simulations for reliability and lifetime prediction

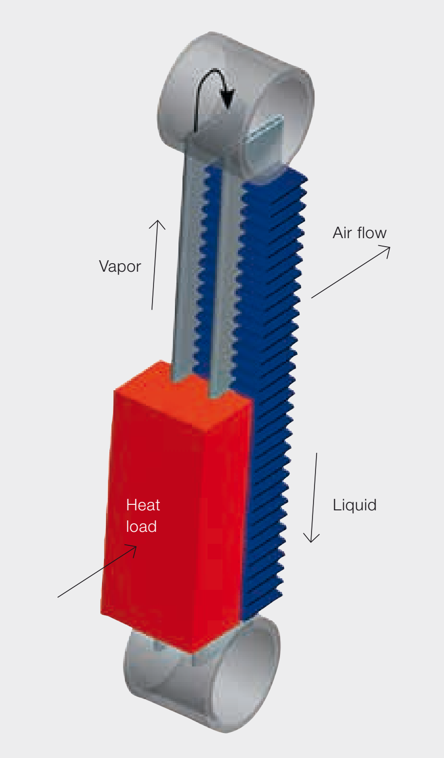
Cooling

Air and water are commonly used for cooling in electronics and accurate simulation tools are available for both (eg, ICEPAK, QFIN).

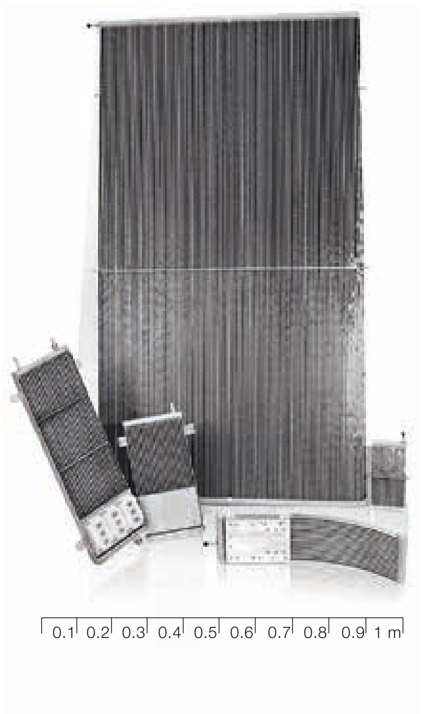
In power electronics, two-phase cooling thermosyphons are a particularly interesting alternative to active cooling meth-

Title picture
Result of COTHEX baseplate temperature distribution simulation

2 COTHEX technology principle



3 COTHEX family (base to air and air to air)



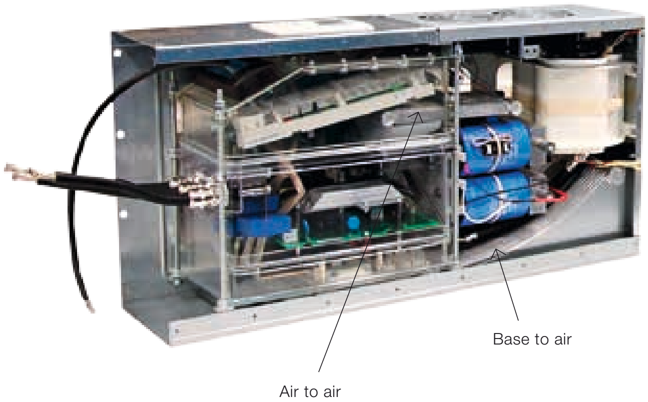
The compact designs adopted to obtain high power densities also increase electromagnetic coupling between different parts of the equipment.

ods [1]. In a thermosyphon, fluid circulates by gravity because of the density difference between the liquid and the vapor → 1. Thus, the use of dielectric fluids and pumpless operation with high boiling-heat transfer coefficients is an attractive combination for the cooling of devices with higher power densities. The method displays higher reliability than pumped water (no moving parts or electrical insulation issues). ABB has developed a compact thermosyphon heat exchanger based on automotive technology. It uses numerous multiport extruded tubes with capillary sized channels arranged in parallel and brazed to a heated baseplate in order to achieve the desired compactness → 2 – 3. The technology calls for new modeling methods, however, as it can presently not be adequately covered using commercial tools. Simulations of two-phase thermosyphons should predict the thermal resistance from heat source to heat sink (eg, ambient air), but also critical parameters such as dry-out (to ensure temperature uniformity), critical heat flux (to avoid temperature runaway), pressure losses or optimal fluid filling. ABB's two-phase thermosyphon model is based on the solving of the mass, momentum and energy two-phase conservation equations. Suitable correlations and models from literature or from university collaborations are used to calculate the pressure drop, void fraction and heat transfer coefficient in the successive sections of the thermosyphon.

Two-phase cooling thermosyphons are a particularly interesting alternative to active cooling methods.

The residuals of these conservation equations are then evaluated and minimized with a suitable minimization algorithm (SIMPLEX). This two-phase flow model is coupled to a finite volume partial differential equation (PDE) solver to determine the heat spreading through the baseplate → title picture. Since there is no pump to drive the fluid inside a thermosyphon, the fluid flow rate and therefore the cooling performances are very sensitive to many parameters such as tube lengths and diameters, heat flux distribution, fluid pressure and the nature and amount of fluid. These simulations

4 Low-voltage drive with one base-to-air and one air-to-air COTHEX installed



For many components accurate high-frequency modeling methods had to be developed specifically.

thus allow the optimal product design to be built while bypassing a considerable amount of prototyping effort ➔ 4.

EMC

Modern power-electronic converters are complex devices in which high currents and voltages coexist with disturbance-sensitive control and communication signals. The compact designs adopted to obtain high power densities also increase electromagnetic (EM) coupling between different parts of the equipment. To provide reliable and safe operation of converters, the electromagnetic compatibility (EMC) of the device must be ensured. Three aspects of EMC have to be taken into account:

- Ability of the device to work in a certain EM environment (immunity)
- Emitted EM noise toward the environment must be kept below certain limits (emission)
- EM interference between different parts of the same device (EMI)

The first two items are a subject of regulations in the form of specific emission and immunity norms. The third item defines internal robustness and reliability of a device.

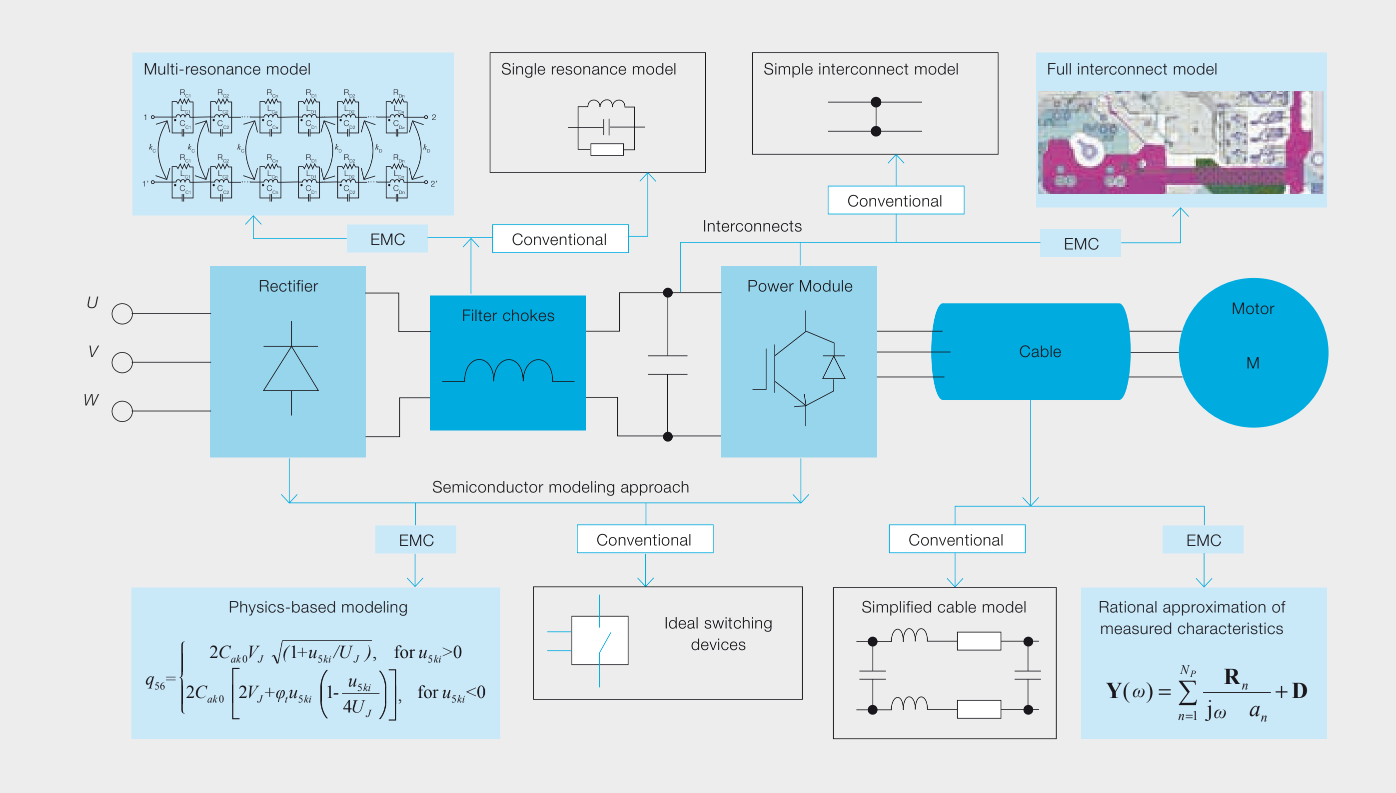
The trends toward compact design, high power density and fast-switching power semiconductors are making the EMC design of power-electronic equipment increasingly challenging. Too often, trial and error is the main approach when it comes to dealing with EMC in power-electronic devices. In such scenarios, measurements are performed on completed prototypes in which layouts and components are already fixed. Modifications are difficult at this stage and typically lead to delays.

In contrast, a smarter EMC design approach starts with system level EM simulations. The advantages of this method are:

- EM effects in the converter and its components can be taken into account at an early design stage.
- HF simulations of the complete converter can help understand and prevent possible EM disturbances.
- Based on EM simulations, optimal filter and layout designs can be achieved using numerical optimization algorithms.

The advantages of the simulation method may seem obvious, but the preparation of adequate converter models is a complex procedure. In order to be able to obtain usable simulation results, both discrete components (eg, capacitors and semiconductors) and mechanical and interconnect structures (eg, heat sinks, PCBs, cables) must be modeled precisely. The overall number of components in the system-level circuit model can easily exceed 100,000.

The different component and interconnect types existing in a converter demand different modeling methods and tools ➔ 5. For some of the components (PCBs, heatsink, capacitors), commercial tools are available. However, for



$$q_{56}=\begin{cases}2C_{ak0}V_J\sqrt{(1+u_{5ki}/U_J)}, & \text{for } u_{5ki}>0\\ 2C_{ak0}\left[2V_J+\varphi_t u_{5ki}\left(1-\dfrac{u_{5ki}}{4U_J}\right)\right], & \text{for } u_{5ki}<0\end{cases}$$

$$\mathbf{Y}(\omega)=\sum_{n=1}^{N_P}\frac{\mathbf{R}_n}{j\omega\quad a_n}+\mathbf{D}$$

> Power converters operating in remote or difficult-to-reach areas are required to continue functioning for decades.

many other components (eg, long three-phase power cables, common mode chokes) accurate high-frequency modeling methods had to be developed specifically [2, 3]. Thus EMC simulations for power electronics applications is growing to a more complex EMC simulation framework. This includes development and implementation of new component modeling techniques and tools (in collaboration with STC → 7), and the know-how surrounding selection and combination of component models into a system-level model, as well as post-processing and analysis of the simulated quantities.

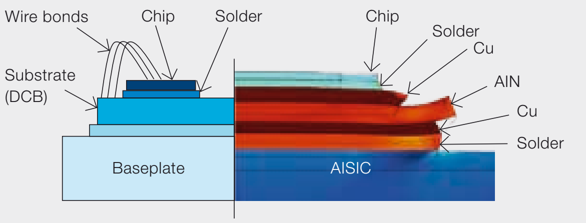
Reliability

Power converters operating in remote or difficult-to-reach areas (such as offshore wind power installations) are required to continue functioning for decades. The location-specific challenges of maintenance and service interventions raise the importance of reliability.

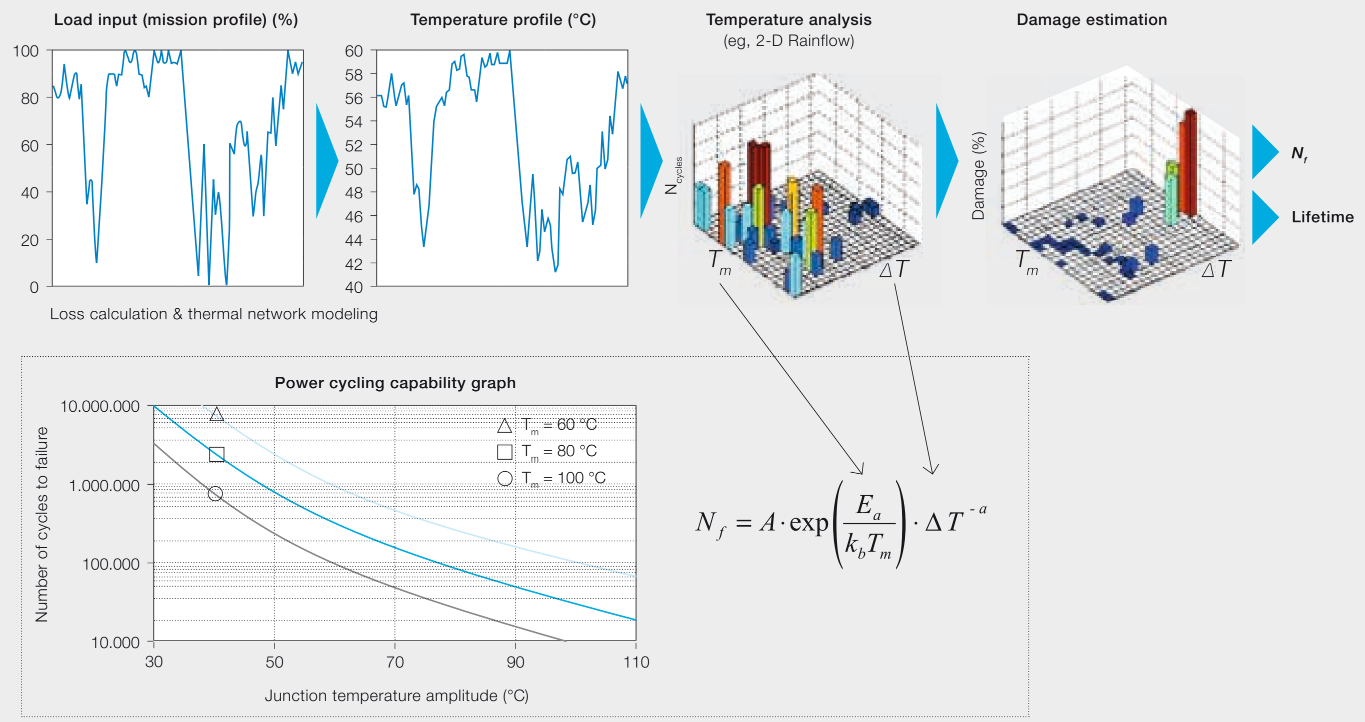
In general, it can be said that a system's reliability is the product of the reliability of its parts. Each part can fail, either due to wear or due to excessive stress, and in doing so can engender system malfunctions. The more the individual parts are stressed, the higher the likelihood of a failure. Stresses can include (but are not limited to) applied electric fields, humidity and temperature.

The heart of every power electronics system is its array of semiconductor switches. Typically they are packaged in power modules providing insulation, internal current distribution and protection. These modules are made of different materials, each with its own coefficient of thermal expansion (CTE) → 6. When subjected to temperature changes (eg, due to load changes) this mismatch in CTE values causes mechanical stress – and ultimately wear – at the interfaces, which can ultimately break. For example, one cause of failure in IGBT (insulated-gate bipolar transistor) modules is the connection between the silicon chip and the attached aluminum bond wires breaking.

Material	CTE ppm/K	length change Δl
Bond wire (Al)	23	
Chip (IGBT) Si	3.5	
Chip Solder (SnPb)	29	
AlN –DCB	10.7	
Substrate solder (SAC)	17	
Baseplate (Cu)	17	



Cross-section schematic of IGBT module. Right: FE simulation showing deformation caused by thermal cycling (100 x saturated). [Source: Samuel Hartmann]



$$N_f = A \cdot \exp\left(\frac{E_a}{k_b T_m}\right) \cdot \Delta T^{-a}$$

Since this failure mode is well understood, manufacturers provide cycling capability graphs for their IGBT modules. These can be used as basis-of-lifetime simulations using the following steps.

- Definition of a possible load (mission) profile: What kind of stresses and environment will the components see in their lives?
- Loss calculation: Losses in the semiconductor switches are calculated from the load profile.
- Temperature profile calculation: In conjunction with thermal network models, transient temperature profiles are calculated for each semiconductor switch.
- Analysis of temperature profile: The temperature profile is analyzed according to the main stress parameters, ie, temperature swings, ΔT and median temperature T_m.
- Damage estimation: For each ΔT and the corresponding T_m the expected damage is calculated from cycling capability curves.
- Lifetime estimating: The lifetime of the semiconductor is given by the time needed to accumulative critical damage.

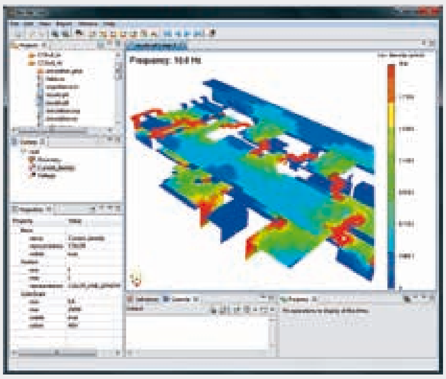
> The more the individual parts are stressed, the higher the likelihood of a failure. Stresses can include applied electric fields, humidity and temperature.

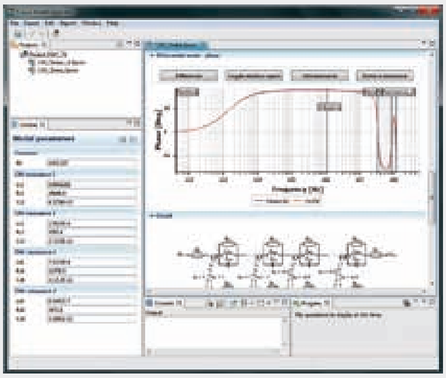
A similar procedure is applied for all other failure modes that may occur. In power modules for example, the solder joints suffer from thermo-mechanical cycling. In contrast to aluminum bond wires, the solder materials experience significant creep. Therefore finite element modeling or other numeric simulations are applied to calculate the damage induced by the applied load profile that finally determines the expected lifetime [4]. Of all the calculated failure modes, the shortest lifetime defines the lifetime of the component (in this case, the IGBT module) and thus the system in which it is used.

Outlook

Enabled by continuing improvements in computing technologies, the size and complexity of simulations will continue to grow. At the same time, advanced software interfacing and scripting tools will allow the coupling of further simulations in different fields. While bringing many advantages to product design and performance prediction, these developments will also lead to increased com-

7 Simulation Tools Center





ABB's Simulation Tools Center (STC) group was established in 2009 in Krakow, Poland. It provides professional power electronics simulation software for ABB. STC's services include:

- Development of dedicated and easy-to-use graphical user interfaces (GUI) for tools and algorithms developed in the frame of research projects in the various ABB corporate research centers.
- Programming of data interfaces between various internal or commercial simulation software to allow for coupled simulations.
- Long-term maintenance of the internally developed tools.
- User support, including tools training, typically teaming up with the scientists that developed the solvers.

The tools developed can, for instance, support design algorithms for new developed power electronics integration technologies (eg, new cooling devices). The availability of such tools significantly accelerates the transfer of new technologies from research into products.

Other tools provide new simulation methodologies and solvers, which are commercially not available. They therefore close important gaps in the simulation landscape, such as for example in the field of electromagnetic compatibility (EMC).

An important aspect of coupled simulations is that results from one simulation (or measurement) can be translated to input models for other tools. One such an example is the "busbar tool" (BBT) software, a dedicated tool for electromagnetic design of power interconnects (busbars). BBT not only provides the relevant impedances, current densities and field patterns, but also does post-processing of mechanical forces and exports busbar macro models for further simulations at circuit level (eg, in SPICE or MATLAB Simulink).

Another example is the "circuit model generator" (CMG) that creates high-frequency equivalent circuit models of inductors, common mode chokes and induction machines using measured or simulated impedances.

Finite element modeling or other numeric simulations are applied to calculate the damage induced by the applied load profile that finally determines the expected lifetime.

plexity in terms of handling the growing number of tools, models and results, and typically will also involve designers in different locations. It is therefore all the more crucial to focus on the necessary infrastructure and to provide long-term maintenance of the various commercial and self-developed tools and models. At ABB, this task is performed by the company's power electronics simulation tools center (STC) → 7.

As a result of the focused use of state-of-the-art simulations, integration technologies will keep pace with the increasing performance of semiconductor devices and their challenges. The future of power electronics applications will thus be characterized by continuous increase of power density, improvement of product reliability and reduction of cost per power.

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