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Design, Simulation and Protection

Integrated architecture approach combining power semiconductor components efficient

A constantly growing global population coupled with higher and higher demand for power has led to corresponding growth in needs for power electronics equipment, especially converters and energy storage systems. Those needs are also expressed in key requirements, chief among them better energy efficiency and smaller footprints. To improve their energy efficiency, power electronic converters have to be pushed to maximum performances while ensuring reliability in production and overall purchasing and operating costs.

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Today's state-of-the-art power electronics converters require the design engineer to employ an integrated architecture approach combining power semiconductor components, like - but not limited to - IGBTs, with passive components such as heat sinks, capacitors, busbars, resistors and fast acting fuses. Focus on the interfaces and an interaction among those components is key in the search for the best compromise between cost and performance.

Mersen Electrical Power has many years' experience in fuses for semi-conductor protection, cooling, and busbar design. The fusion of three leading brands in those components - Ferraz Shawmut, R-Theta and Eldre - into a single group, Mersen, offers the designers of power electronics equipment much more than a single supplier. They can benefit from Mersen's skills and expertise throughout the process of converter designing. Mersen Electrical Power's position on the market is that of a partner in upgrading the performance of such systems, reducing their footprints, and improving safety and reliability.

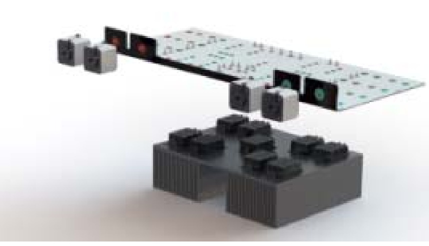

Figure 1: Power electronics integrated architecture

Mersen can guide power electronics designers directly toward the right choices in an integrated architecture approach. We provide our know-how of passive components in the earliest stages of design, giving the customer an opportunity for the best possible discussion of technical issues to ensure their exact needs are met.

Cooling is the foundation of an integrated architecture, since the active semi-conductor components are installed directly on the cooling unit, and therefore defines the dimensional and mechanical outlines of the system. Next, the busbar connects this active heart of the system electrically to all its passive components: resistors, inductors, and capacitors. Finally, fuses are the system's ultimate protection, guaranteeing the safety of both the equipment and the people working in its vicinity.

When the time comes to confirm all the decisions being made, simulation – a crucial complement to full scale tests - is a handy tool that considerably shortens development times.

Mersen and you : straight to the optimized design

The electronic design determines the heat generated by each IGBT, so the cooling device and busbars are the first passives to be selected. The heat sink answers thermal needs but also serves as a base frame for the converter's main power switch. Furthermore, heat sink thermal performance combined with the thermal dissipation of each power semiconductor will influence the converter layout and thus the busbar design.

The first building block of the power converter is the selection of the cooling solution. The challenge is to cool down the semiconductor in a dynamic way. It looks like a thermal issue but in reality it is a trade-off between the thermal performances, the pressure drop

Figure 2: Liquid-cooled cold plate

in the system, the available fluid velocity and the mechanical constraints. Additionally, no two cases are the same and, depending on the customer's design experience, habits and constraints. To answer this challenge, Mersen has developed years of experience customizing each design to the customer application while applying manufacturing processes to drive down the manufacturing cost.

Figure 3: IGBT modules placed onto the heat sink

Once the IGBT modules have been placed onto the heat sink to allow for proper thermal dissipation, the designer is confronted with how to interconnect them with the lowest inductance power distribution path possible.

In high current power electronics applications, low inductance power circuit is a critical element for safe and efficient operation of IGBT modules. If not addressed early in design, the stray inductance on the total DC bus connecting the DC capacitor bank to the inverter devices (commutation loop) can result in several undesirable consequences. For example the hard switching converters' excessive transient overshoots create the potential of increased device heating during switching, leading to unnecessary use of large heat sinks or tuning the converter to lower switching frequency and therefore larger, more expensive, passive components like capacitors. Unnecessary stray inductance is an obstacle for design engineers, who need interconnection distances between switching devices in order to dissipate the heat generated by power electronics semiconductors.

The following will address the different alternatives.

Instead of the use of a wiring harness on DC bus amperages approaching 150 amps and above, the use of multiple interconnect layers is the solution to large current carrying capability, low stray inductance, high frequency applications, smaller space requirements and reliability issues. For the traditional power distribution topology of IGBT modules, the use of side-by-side busbar conductors is still common in today's industry. However, side-by-side conductors do not provide the lowest effective mutual inductance for the distribution path. There is some mutual inductance cancellation along the adjacent edges of the conductors, but to minimize mutual inductance, these busbars would need to be placed directly on top of one another, not side by side. Designers can further lower the mutual inductance by placing the wide DCplus conductor plate on top of the wide DCminus plate, separating them with a thin dielectric material. This provides the greatest surface area for flux cancellation. Prototyping using this method is frequently done and provides the components in the inverter with enhanced electrical characteristics through lower inductance. Separate bushings can be placed on the bottom contact surface of the top plate to bring the power down to the IGBT module located below the bus. As these types of loose bushings will seldom lie completely flat against a conductor plate, this could result in an increased contact resistance around the bushing.

Figure 4: Lamniated busbar for solar PV inverter application

Mersen custom-designed laminated busbars provide the lowest possible effective inductance for a system. This is made possible by laminating a thin piece of dielectric material between the DCplus and DCminus plates. Laminating the dielectric plates together under heat and pressure keeps the levels consistently close, allowing for maximum mutual inductance cancellation directly along the power distribution path. The closer the plates and the more uniform their separation throughout the length of the bus, the more mutual cancellation can be achieved. To reduce the number of components in the system even further, the AC conductors can also be laminated into the bus assembly. This will not decrease the mutual inductance cancellation of the plus and minus plates but does enhance overall bus design. Once laminated, the resulting rigid structure is capable of withstanding several hundred pounds of cleavage strength and several thousand Volts across the conductor plates. Making the electrical connection to the power components becomes a matter of selecting from a range of metal-forming options: embossments, soldered bushings, press-fit bushings and formed tabs. Permanently incorporating these contact surfaces into the structure permits low contact resistance between the bushing surface and the conductor plate.

Copper alloy is the standard and recommended conductive material in the majority of IGBT laminated busbar applications given its low resistance characteristics and cost, but Aluminum, brass, beryllium copper, or phosphor bronze may also be specified. The accepted value for current carrying capacity of copper is 5A/mm2. To determine the cross-sectional area (in mm2) required to carry the steady state current, divide the steady state current of the DC bus by 5A/mm2. In this scenario the copper's temperature rise will be 30°C above ambient temperature.

Proper selection of dielectric material will ensure the lowest mutual inductance in the laminated structure. A common misconception in laying out a laminated structure is that a very thick dielectric is needed to meet voltage requirements. The laminated structure has materials in a sandwich; designers need to allow sufficient insulation overlap beyond the edges of the conductor to eliminate arcing between the conductors.

Once the conductor size and insulation is specified, the designer must determine how to distribute the power in and out of the IGBT module and what the physical layout will look like. Various methods may be used to interconnect IGBT modules with the laminated busbar. Once the DC conductor plates are laminated into an assembly, the assembler may simply place conductive bushings/ spacers under the contact surfaces of the busbar to the IGBT tabs. The different height potentials required for the bushing/spacers may cause an assembler to place the wrong bushing/spacer in the inverter during assembly. The solution to this potential problem is the use of embossments and soldered-in bushings. With the contact surfaces incorporated into the laminated busbar, the designer insures the proper connections to the IGBT tabs while maintaining a low voltage drop contact. The DC bus conductors can be effectively embossed to two times the material thickness, and the embossment slotted if different IGBT terminal spacings are required. The current carrying capacity of the embossment is reduced when the conductor material is stretched beyond two conductor thickness. The soldered-in bushings can extend down and/or up to accommodate the creepage barrier on some IGBT modules and interconnect driver circuits and snubber boards. The use of a tab with slotted holes can also be used to interconnect IGBT modules with built-in creepage barriers. However, the mutual inductance will increase when the DC plates are separated.

Once the basic structure made up of the heatsink, active semiconductor switches, and busbars is defined the integration and optimization of the remaining passive components will take place. Here again, the expertise of the components manufacturer is critical in achieving the best overall performance.

Ultimate protection against excessive damage

Shortcircuit faults in power electronics equipment will cause excessive damage, or in the worst case, explosion. Electronic protection against overloads and shortcircuits is normally embedded in new power electronic semiconductors but backup fuse protection is still needed to ensure safety in the event of failure of these systems or the device itself.

When selecting semiconductor fuses, the designer must reconcile opposite deliverables. During normal operation we want low Watts, unlimited lifetime expectancy, low body and terminal temperatures, and of course low cost but we also need the fuse to operate as fast as possible, with minimum let-through energy and arc voltage when everything else has failed. Many of the requirements (energy let-through by the fuse, commonly known as I2t, life cycle expectancy, connection, fuse opening indicators etc.) conflict with each other, but new fuse designs as well as new manufacturing processes have helped reconcile them. Furthermore, new simulation tools in addition to Mersen's field specification engineers have accelerated fuse selection for demanding power electronic applications like drives and rectifiers.

Figure 5: Typical fuses for the protection of power semiconductors

A typical semiconductor fuse consists of one or more silver or copper or thrulay (series of silver and copper) elements enclosed in a fuse body, either welded or soldered to the fuse contacts/terminal. Sand filler plays a major role in fuse performance. It quenches the arc by absorbing the energy during arcing time and serves as fuse element cooler during normal operation by conducting the heat away from the element, through the fuse body and to the medium surrounding the fuse. Short fuses will transfer more heat through the terminal. Long fuses will transfer heat through the fuse body. Fuse "savoir faire" is how well you manage the fuse element thermal equilibrium. Running with the element hot will make the fuse fast opening but subject to premature opening. Running the element at a lower temperature will lead to a long-lasting fuse, but when needed, will it protect? Fortunately, we current rate fuses to achieve the best trade-off between clearing, operation, and cycle performances.

The fuse is a calibrated current-carrying device designed to open under specific conditions. The numbers of notches in series in the fuse element will define the fuse operating voltage and the total cross section of parallel elements will define the rating of the fuse. The element material, mass, and notch configuration, along with the surrounding materials, all contribute to fuse performance. The narrow path for the current will lead to higher current density and thus to higher heat generated at the notches. The total notches cross section will define the pre-arcing I2t needed to melt the fuse element; in other words the energy needed to melt the narrow path. Under sustained overcurrent, the fuse element generates heat at a faster rate than the filler can conduct it away from the element.

At the end of the pre-arcing time the fuse switches to arcing mode. The fuse will develop an arc voltage higher than the source voltage and this will force the current to go down to zero. This period is call the arcing time. During this period the fuse will have to dissipate the energy supplied by the source as well as the energy stored in the circuit, mainly ½ LI2. The total energy let through by the fuse, known as total I2t, is the result of the sum of the prearcing I2t plus the arcing I2t. Those values are supplied for our fast acting semiconductor fuses. The normal condition for shortcircuit protection is that the total I2t integral let through by the fuse when clearing the fault must be less than the I2t which produces system damage. For example, for IGBTs the appropriate value is the level of I2t which causes case rupture.

Figure 6: Fuses with low inductance for IGBT protection

Increased voltage for IGCT and IEGT protection, demand for lower I2t for IGBT protection and large rectifier protection have led to new fuse ratings and performances. It is not rare anymore to see semiconductor fuses rated at 10kV 1000 A with low inductance. Fault simulation will help to calculate the melting time, and will give the total I2t to be compared with the semiconductor housing's I2t. If needed for demanding applications, our capacitor discharge lab will backup simulation/calculation by actual testing. Also, Mersen's High Power Test Lab can be used to determine the semiconductor's true housing I2t value.

Simulation to boost development processes

Historically, passive components were developed based on hand calculations and comprehensive know-how. However, as designs grow increasingly complex, analytic calculations become impossible to solve, especially from the thermal standpoint. To shorten time to market thermal simulations are becoming a decisive tool in developing a custom component.

Why use simulation? The most reliable way to make sure that a component respects its specifications is to build a prototype and test it in operating conditions. But as reassuring as this solution would seem, it also presents several drawbacks. Each design is unique: metal cutting and machining operations, surface finishing, tools to bend some intricately shaped products, insulating material layers specially crafted for the tested geometry ... All those additional costs cause the global price to increase for a component that might not be validated by the tests.

Building a prototype is also time-consuming and that's why simulation is a handy tool to boost development processes. By adding pre-test steps in the conception phase, design flaws can be spotted and eliminated before going through the prototype manufacturing process. Overheating areas or overly thick plates are not always easy to determine by calculations. Computer generated temperature maps are very appealing and easy to understand: "a picture is worth 1000 words". It is more encouraging for the customer to get preliminary test results before ordering a prototype, and to have a back and forth exchange to adjust the initial design. However, simulation is not meant to replace tests entirely. The quality of the calculated results is only as good as the input data and understanding of underlying physics.

Mersen uses COMSOL Multiphysics finite element software. The finite element method is based on iteratively solving equations locally until overall stability is reached. To be able to take into account the geometry, we need to divide spatial domains (or surfaces in the case of a 2D problem) into small meshes; for each knot we calculate the value of each studied variable at each iteration (in the case of a stationary study) and each time (in the case of a transient study). A suitable mesh is crucial: too coarse a mesh might hinder the convergence of the simulation, but the number of elements and knots is limited by system memory and computing capacities. In COMSOL the mesh is built automatically, depending on the physics used in the model.

The next step is very important: defining the physics involved. Let's take the busbar example. In the case of our thermal simulations, we are aiming to prevent the busbars from reaching high temperatures caused by Joule heating, 105°C being the typical PET limit, or a limit set by the end customer. The current distribution is determined according to customer specifications. The easiest way to model it is to calculate current r.m.s. values and to treat them as direct currents. With this approach, we can set a stationary model of current repartition.

When currents are more complex, especially currents of different frequencies going through different inputs or outputs, a transient model is required to account accurately for the fact that currents of different frequencies don't add up directly. The electrical phenomena timescale being different from the heat transfer timescale, a transient study must be done to calculate the current density map before the stationary heat transfer study. Current density leads to heating. Cooling is usually accounted for by three phenomena.

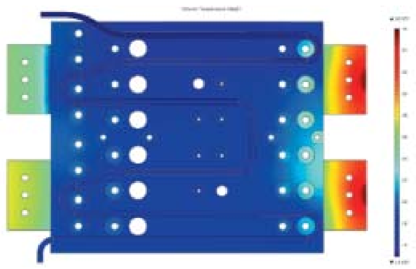

Figure 7: Thermal simulation for a water-cooled busbar

The first is conduction, addressed by solving the heat equation. The second is radiative heat transfers calculated from the Stephan-Boltzmann law. Plastic radiates much more than oxidized metal, which radiates more than polished metal. The third is convection and is less straightforward.

Simulating a complete air volume with fluid mechanics is possible, but memory and computing power can be expensive. Meshing the air is again very difficult, as the air mesh has to be continuous with the busbar mesh. The finite element method is not the best to solve this kind of problem. The best way to address it swiftly is usually to calculate the mean heat transfer coefficient depending on temperature, based on the customer's operating conditions.

Fluid mechanics is, however, used in the case of water-cooled busbars, by modeling laminar water flows in the pipes. Conduction means a water cooled busbar will take the heat away from the circuit. Of course, well defined material properties and current condition are paramount to running an accurate simulation. Simulation can, in fact, vary significantly, depending on environmental conditions (temperature, pressure, etc.) and the metallic alloys and dielectric materials (PET, Nomex, Kapton, etc.) used. To achieve an accurate simulation will require clear understanding of the final application.

As we saw earlier, thermal simulations can be used in numerous situations. The earlier the simulation is integrated into a project the better. Computer calculation can also intervene later in the product life-time, to determine causes for product failure, or to study if a given design could be used for another application and/or higher current rating and/or ambient temperature conditions. The main goal is to validate if the proposed design meets customer specifications.

Simulations are perfect to provide precise information to the customer. Having accurate and detailed information on each available solution is extremely valuable when determining key characteristics for a prototype.

Figure 8: Power electronics assembly with the integrated architecture approach

To conclude, in today's Design for Manufacturability (DFM) environment, both design performance and manufacturing costs come into play when design engineers lay out systems. Component count, assembly time, and system size and performance are all factors that must be taken into consideration. The Mersen cooling, busbar, and fuse expertise support designers to optimize all of the components in a power system in an integrated architecture approach. From the outset and throughout the project, our team of solutions engineers, our product offering, and our simulation and testing capability can provide critical added value to the converter designer.

http://ep-uk.mersen.com/solutions/power-electronics-solutions