“Power under the hood”
Increasing power density of inverters with a novel 3D-approach

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Abstract: “Under-the-hood” electronics are a challenge for all automotive engineers. Especially if the device is dissipating heat and requires liquid cooling and high voltage. Hybrid electric vehicles are such a demanding application. When continuous power exceeds a few kW, liquid cooling becomes mandatory to maintain sufficiently low junction temperature of the power devices (e.g. IGBTs, MOSFETs). And low temperature is a key to achieve expected reliability targets.

A major contribution to the state-of-the-art of liquid cooling technology is the well accepted ShowerPower® approach. A guiding baffle for a stream of cooling liquid can successfully be applied directly to a baseplate or direct substrate cooling. Hence the necessity for metal pin-fins in a cooler or other complex geometries can be eliminated by the proposed “metal-to-plastic” conversion.

Many designers, especially in the automotive environment, are striving for a robust separation between water and high-voltage compartment, similar to traditional planar coldplates. In this article, we present the combined advantages of both approaches. The safety and convenience of a classic closed cooler is coupled with the efficiency of ShowerPower®. In conjunction with a stacked assembly, a significant increase in power density can be achieved.

Our investigations compare the new approach with recent designs from Japan and classic planar layouts. In consequence, it combines the ease of assembly and robustness of the planar way with a double power density of more complex stack designs.

1. Introduction

New European and global CO_2 -emission-targets for passenger cars are setting a further challenge for the automotive industry. Electric propulsion, both in combination with internal combustion engines and as an exclusive battery-electric drive system, are expected to make up for at least a reasonable fraction of the future powertrain mix.

All automotive OEM, although struggling from a more or less severe sales crisis, are busy to present concepts cars and new series vehicles. And the much-admired first mover Toyota is not getting tired to further develop electric propulsion designs for its consecutive new model platforms.

2. Current technologies: Planar module cooling

The classic setup of a power module can be observed in today’s hybrid electric vehicles. Limited available space in the engine compartment is combined with severe temperature and vibration loads. Often, the packaging space for HEV inverters has to follow restrictions of an existing car platform that was predefined and layed out in the days before electric traction was an issue.

The key target conflict includes the following parameter

- Stringent cost targets
- Limited packaging dimensions
- Outstanding reliability targets

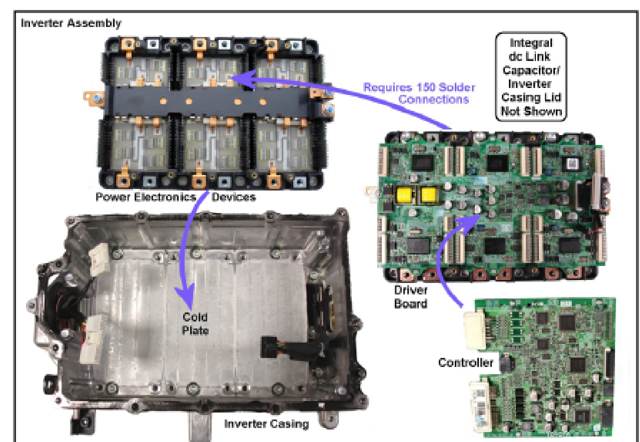

Figure 1. Traditional Inverter Assembly [1]

Courtesy of Toyota / US D.o.E

A way to solve all three issues is an optimized thermal resistance and a highly performant cooling of semiconductors.

Traditional traction inverter designs comprise a frame-based power module. Figure 1 describes the design of a Toyota “Camry HEV” device. The metal baseplate is coupled to a closed loop heatsink via thermal interface material TIM (“thermal grease”).

Figure 2. Closed cold plate cooler [2].

Courtesy of Toyota / US D.o.E

Underneath the bottom plate of the cast aluminium housing a complex meandering structure can be found to increase surface and cooling efficiency (fig. 2). The key advantage of this design is its ease of assembly in a “layer-cake” approach. Moreover, the cooling liquid is well separated from high voltage electronics and the inside of the ECU by the rigid cast aluminium housing.

A disadvantage of this design can not be neglected: Due to its limited thermal conductivity, the thermal grease is responsible for a large share of thermal resistance R_{TH}.

Moreover, a two-dimensional design does not utilize space most efficiently and therefore, power density is restricted. Due to design limitations the fill factor of semiconductor surface is usually not higher than 15-20% of the baseplate surface.

The baseplate itself plays an important role as a heat spreader. It allows for vertical and lateral distribution of heat, before the thermal current passes the “barrier” of thermal grease. For prolonged module lifetime, baseplate material should also have an appropriate thermal expansion coefficient C_{TE} in order to minimize thermomechanical stress of solder joints between baseplate and the ceramic substrates.

3. Next Generation: Stacked cooling

A more advanced design approach can overcome restrictions of traditional two-dimensional layouts. An interesting example was published by Yasui / Denso in 2008. The devices can be found in Toyotas top-of-the line hybrid vehicle “Lexus LS 600 h”. Here, power density benefits from a 3-dimensional stack (see figure 3-5).

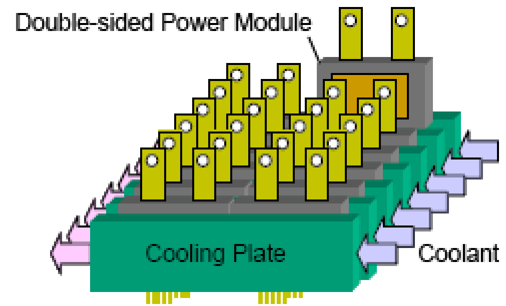

Figure 3. Stacked array of modules [2].

Courtesy Denso

The high count of layers is combined with an advantage of a double-sided cooling of IGBT and diodes. The power modules themselves are very flat and therefore space-saving. In consequence, a fine mesh of heat-dissipating devices and heat-sinks is created within the stack.

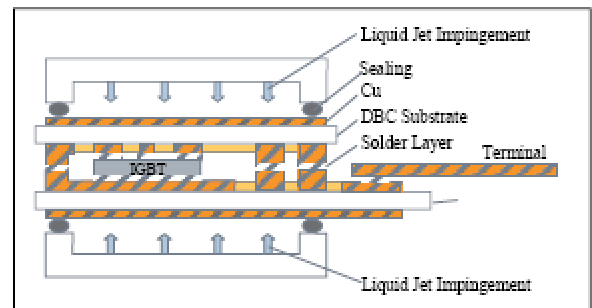

Figure 4. Denso solution of double-sided cooling.

Courtesy Denso

An important feature of baseplate-less modules with direct cooling applied to DBC substrates is the considerably reduced thermal mass. This leads to a very light-weight and compact design. On the other hand, the devices have to work without substantial heat-spreading and the dynamic behaviour needs to be observed in more detail (fig. 4, 5).

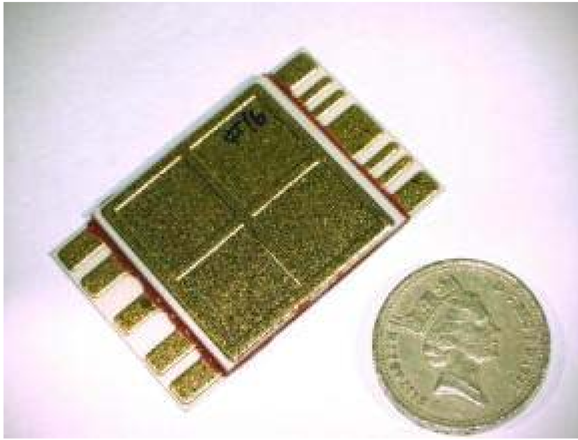

Figure 5.Denso power sandwich.

Courtesy Denso

The baseplate-less power modules are integrated in an elastic cooler that basically reminds of the wide-spread heat exchangers of air-conditioning systems.

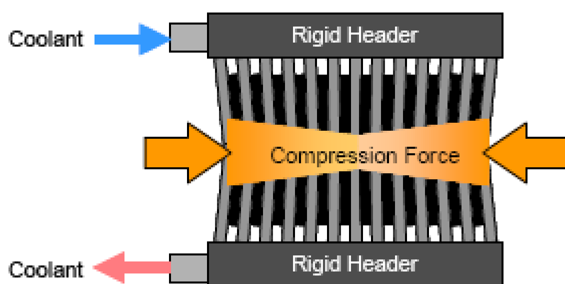

Figure 6. Denso approach of clamping modules.

Courtesy Denso

This stack approach comprises several advantages. The power density benefits from three basic factors:

- Small displacement / volume of modules
- 3D-stacked geometry
- Double-sided cooling

Moreover, the geometry has further positive side effects:

- Power terminals are concentrated on one side of the module block, allowing for a low-inductance and compact busbar
- Small signal terminals are positively concentrated on an opposite side allowing for a clean separation of drivers and control electronics and reduce risk of electromagnetic interference.

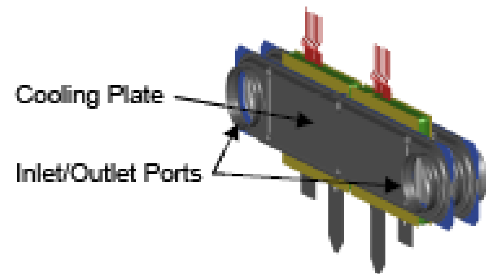

Figure 7. Sandwich design of power modules.

Courtesy Denso

A number of challenges have to be mentioned, too:

- The minuscule cooler built from sheet metal includes a profound length of sealings or welded seams, making the design vulnerable for leakages
- Assembly is complex and the high number of very small “modules” gives only modest advantage of integration compared to discrete components
- Clamping the modules with external force can lead to undesired bending of the heat exchangers structure

Usually there is a lot of psychological reluctance stopping engineers from bringing liquid that close to or into a high voltage device. Once a leakage has occurred, arcing can destroy the inverter.

4. Combining ShowerPower® with a stack

As discussed, standard-technology power modules arranged in planar assemblies often take up a considerable amount of space in the electronic control unit (ECU).

Utilising the latest power module technology will help optimising the designs of the ECU’s. A specifically promising new manufacturing technology for power modules is the transfer mould technology offering very compact and rugged power modules. These modules are especially well suited for the harsh conditions characterising the under-the-hood environment of modern automobiles.

But still planar arrangements, even of transfer moulded power module assemblies, require a considerable amount of space.

A paradigm shift is to think 3D.

Going into the third dimension

Thinking of the power modules as building blocks, 3D arrangements of power modules in a stack give a number of benefits compared to a standard planar assembly.

The simplest 3D arrangement is a back-to-back assembly where modules are placed on both sides of a liquid cooler.

Such a “semi-stack” arrangement is more compact than the planar one, but the full benefits of the 3D possibilities arise when the modules are stacked completely. Additionally double sided assembly processes complicate the manufacturing flow.

Brief description of the elements of the concept:

The ShowerPower® cooling concept offered by Danfoss Silicon Power seems very well suited for cooling a stacked assembly of transfer moulded power modules. The ShowerPower® principle offers the possibility to cool even large power modules homogeneously and stacking the ShowerPower® coolers brings this total thermal design freedom into the third dimension. For more information on the basics of ShowerPower® see (7).

The concept is based on the following elements:

The modules

The concept is envisioned for transfer moulded power modules that are especially well suited for the purpose: the transfer moulded power modules are planar with low building heights, the power- and control terminals and are very rugged and will withstand the high mechanical pressure necessary for ensuring a proper thermal contact to the heat sink. The low building height of the modules makes it possible to realise a very compact design of the stack.

The heat sink

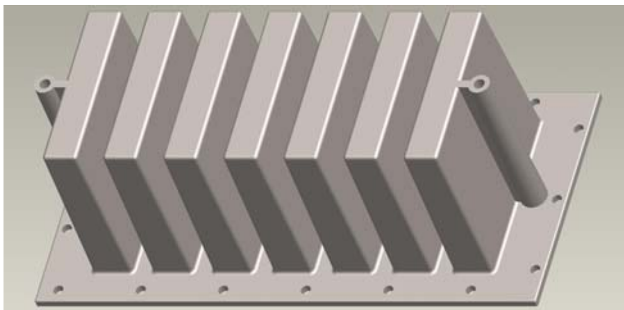

Figure 8. The fin structure of the heatsink.

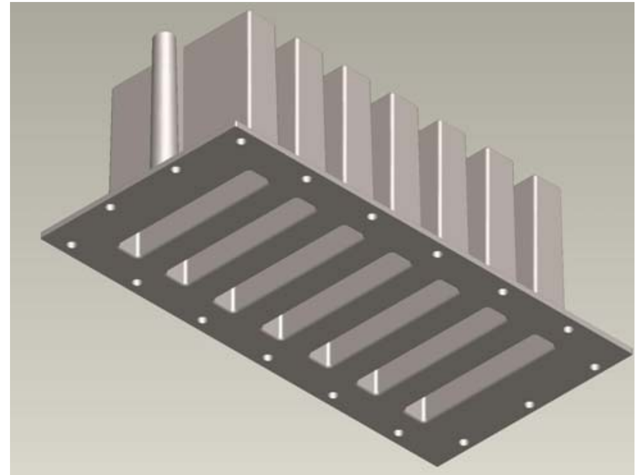

Figure 9. The heat sink body featuring hollow fins.

The figure shows a heat sink with hollow fins; the fins are arranged in such a way that the power modules can slide in between two fins. A plastic wedge ensures proper thermal/mechanical contact to the fins.

The thickness of the walls can be tailored to the required dynamic response of the layer system consisting of the moulded power module, a TIM-layer and the aluminium cast: Thick wall designs (>5mm) for Start- / Stop-applications and thin walls (~2mm) for minimized R_{TH} and silicon surface.

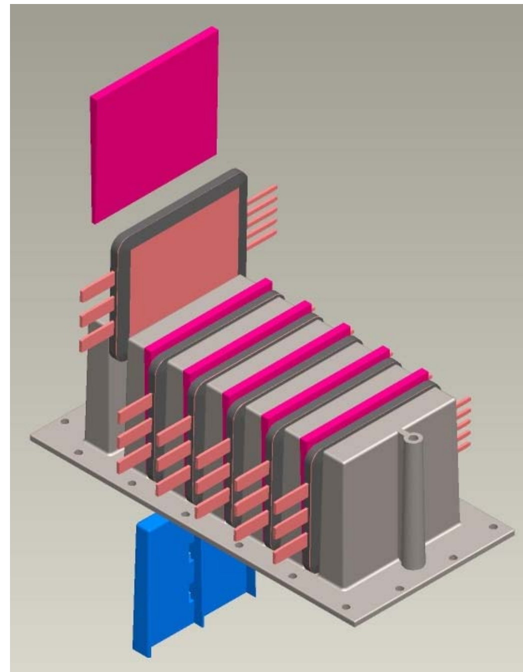

Figure 10. The assembly of the power modules and wedges.

A fin thus has two functions: it cools the power module and presses the next module against the next fin, etc.

The ShowerPower® insert

The ShowerPower® insert, acting as a distributor and turbolator, guides coolant to positions directly underneath the chips of the power modules. The ability to tailor the cooling will enable an optimal thermal design of the whole cooling system.
A ShowerPower® plastic part is inserted into each of the hollow fins of the heatsink.

The ShowerPower® insert can be designed for either single sided or double sided cooling. This depends on the overall stack-concept i.e. whether identical modules are placed sequentially or if modules are arranged in pairs back-to-back. The pictures below show the single-sided version.

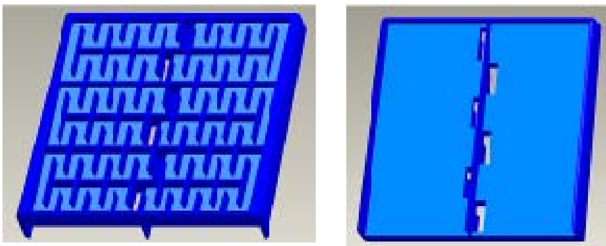

Figure 11. The ShowerPower® part, front and back.

Manifold part

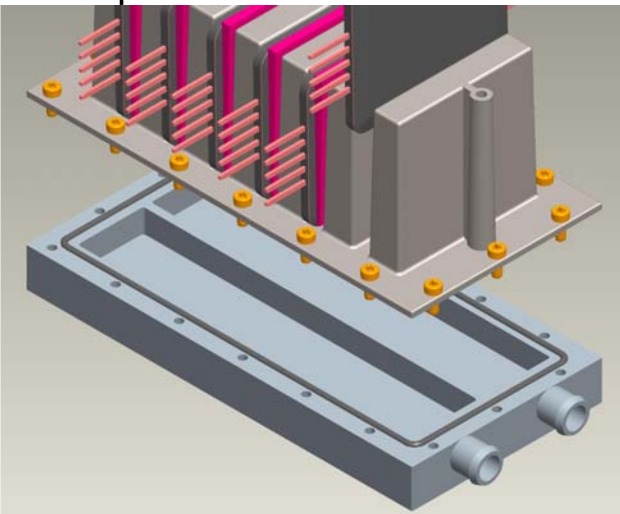

Figure 12. The internal manifold structure ensures equal flow to the individual fins of the heatsink.

Due to the simplicity of the ShowerPower® insert shown above - having two cooling cells only in the horizontal direction, the manifold structure is simply having two chambers only. The arrangement of the manifold structure, which is integrated into the bottom part, ensures that all modules are cooled equally and the ShowerPower® inserts ensure that all chips are cooled equally. Alternatively, the ShowerPower® parts and / or the manifold structure can be designed so that chips running especially hot are taken care of. In other words there is a total design freedom in 3D so that the cooling of all chips in all the modules can be tailored individually.

Fixing parts

It is possible to keep the modules in place with a permanent pressing force against the heat sink by a simple bridge assembly, pressing all the modules and wedges into the grooves. The bridge can optionally be equipped with springs.

Thus a simple bridge and two screws are needed for keeping the modules in place under a permanent pressing force that gives an optimum thermal contact to the heatsink.

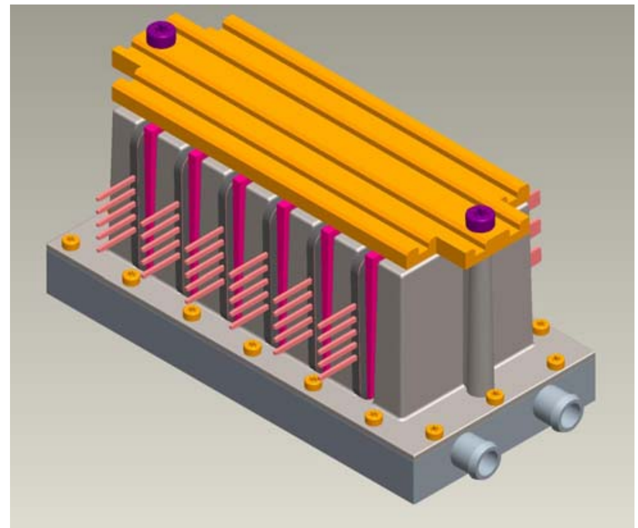

Figure 13. The internal manifold structure ensures equal flow to the individual fins of the heatsink.

The modules can be arranged in several ways between the fins: pair wise back-to-back or sequentially with one module only between fins.

5. Conclusion

Finally, it can be stated that a folded power module geometry can help to approximately double the utilisation of space in an inverter assembly. It is not necessary to break down the module into multiple single switches and more than 6 layers. The

optimum or "sweet" spot is expected somewhere between a double-face design and a 6-layer stack. It can be tailored to the required circuit topology.

The pathway of optimization can be found in a holistic way including the design of the liquid cooler as well as busbar and driver geometry.

The attractive feature of the folded stack is, that it is an integral part of the cast aluminium housing. The casting does not need to include complex structures, e.g. fins.

The required sealing length for the coolant is reduced to a minimum in order to minimize leakage risk. Due to the specific properties of ShowerPower® inserts, the cooling pockets allow a thermal transfer at a similar good level of planar designs.

Therefore, the proposed approach is a viable and cost efficient way to increase power density in an automotive traction inverter.

6. References

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