Custom Power Module Solutions for Automotive Traction Inverters

- the basis for lower cost, higher power density and improved reliability

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Abstract

Conservatively designed, bulky, monolithic power modules have so far been characteristic elements of automotive traction inverters. These designs are not efficiently scalable. To support the long-term commercial viability of hybrid electric vehicles (HEVs) and electric vehicles (EVs), the US Department of Energy (DOE) published technical target requirements for the electrical drive train (motor, inverter, battery) of a 55kW system for 2015 and 2020.

To meet these requirements for a traction inverter, a significant step towards higher power density at the desired lifetime and acceptable cost is needed. However, vehicle mission profile and drive train architecture cause characteristic stress patterns on the power modules' semiconductor representing a limitation in life time. Advanced module and cooling design provides an answer. This paper provides examples of a new series of customized power module solutions that combine scalable, reliable and cost competitive power module packaging technologies with advanced liquid cooled thermal management solutions.

Furthermore, an outlook is provided for further improvement potential in power density and reliability of this technology through scalable 3D module configurations and 2-phase liquid cooling.

Keywords: IGBT power module, liquid cooling, ShowerPower®, thermal stack, mission profile

1. Introduction

The first generation Toyota Prius was introduced in 1997 in Japan (2001 worldwide), making it the first mass-produced hybrid electric vehicle. In 2010 the cumulative worldwide sales reached 2 million units, now in its third generation. A variety of additional hybrid electric vehicles primarily out of Japan but recently also out of the US, the European Union and Korea made their market debut since. In part spurred by the success and acceptance of the Prius and it's family members.

With the broad introduction of HEVs in basically every OEM's model line-up, e-traction and all associated technologies are now scrutinized to meet the pressure for lower cost, which is in part expressed in the requirement for higher power density and an increase in efficiency. Improvements in these areas are important to attract a broader customer base and to assure commercial viability for the OEMs.

At the same time the market continues to push reliability requirements for automotive drive trains in general. E-traction systems have to be on par with their combustion engine counterparts even though they add complexity to the drive train.

For automotive traction inverters, multi chip power modules represent the key component impacting cost, reliability and efficiency of the inverter.

This paper shows how advancements in bonding, joining and cooling technologies lead to a new generation of compact power modules. These new types of lean designs trigger a challenge for the thermal behavior of such modules stemming from the dynamic mission profile of an electric or hybrid-electric vehicle. The result is an optimum trade-off between cost, reliability and performance

2. Challenges

2.1 Cost – Power Density and Efficiency

To meet the long-term commercial viability of electric (EV) and hybrid-electric vehicles (HEV), all system components within the drive train will have to be cost reduced. At the same time an improvement in efficiency is desired in order to offer longer battery life and with that improved fuel consumption of the vehicle – more value to the end customer.

For the power electronics the US Department of Energy (DOE) published technical target requirements for power density (PD) of a 55kW system for 2015 and 2020 (Figure 1).

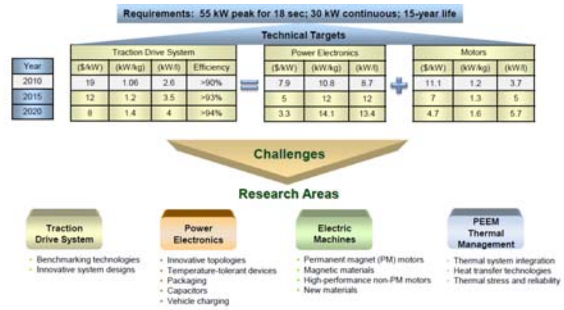

Figure 1. DOE technical target requirements.

In order to meet these targets, significant steps to reduce size, weight and complexity of the power module are required. Semiconductors, typically IGBTs and Diodes, are the key cost contributor in a power module. Semiconductor manufacturers have been able to continuously shrink the size of these components and improve manufacturing processes and with that the cost. Unfortunately, current density within power semiconductors cannot be increased by a similar rate compared to logic gates in microelectronics. Allowable semiconductor operating temperatures are limited by material properties and limitations in bonding and joining technologies.

2.2 Reliability, Lifetime

Typical automotive warranty for the drive train covers up to 100,000 miles. The trend is generally increasing. At the same time, the required operating temperatures for under-the-hood electronics range between -40ºC and +125ºC. On top of this, electric or hybrid electric architectures pose a challenging mission profile for the traction inverter. A typical current pattern in hybrid applications can range from a few hundred milliseconds (i.e. engine start) to several seconds for dynamic acceleration.

Each specific temperature cycle within the mission profile – short, medium, long – poses a lifetime limitation to the power modules' mechanical design. Short temperature cycles are critical for the top side interconnect, typically Al wire bonds. Medium temperature cycles are detrimental for the interface between the semiconductor and the substrate and long temperature cycles are most damaging to the large solder joint between the substrate and a heat spreader (Figure 2).

A thorough analysis of the mission profile of the individual application allows the power module manufacturer to translate the inverter working hours into expected lifetime of the power module.

Once this analysis is complete, the optimum semiconductors can be selected. To avoid having to derate the costly semiconductors, improvements in the module design or the cooling approach must be considered.

The result is an optimal balance between cost, reliability and efficiency.

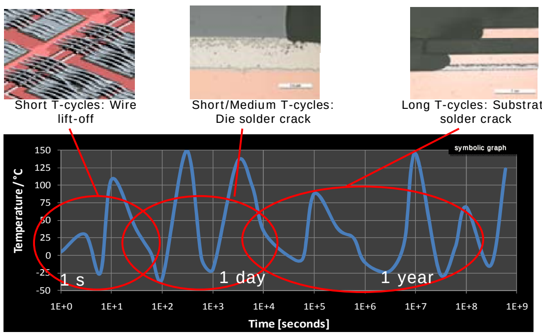

Figure 2. Typical traction inverter mission profile with corresponding failure mechanisms in the thermal stack of a power module.

3. Molded Power Modules

Traditional frame based power modules in conjunction with metal or metal-matrix base plates have for several years been the design of choice for the majority of traction power modules. They offer mechanical robustness and adequate thermal behavior. Frame based modules can integrate a full inverter power stage in a single power module. The base plates, due to the thermal mass, provide proper thermal spreading and buffering which is especially desired in mechanical designs with a non-optimal thermal stack. However, frame based power modules in automotive traction applications show also some significant limitations. Designs are often not scalable and package outlines are found to be bulky and difficult to integrate where space is a sparse resource.

Molded power modules significantly reduce complexity compared to the traditional frame based designs. Here the power-semiconductors are attached to ceramic substrates. Terminals to the outside are created by a stamped metal leadframe. The complete module is then encapsulated with an epoxy mold compound, similar to discrete components. The signal and power terminals in a custom design are configurable depending on the interconnect preference of the customer. Solder pins or press fits are only two of several possible options.

To allow for scalability and a small power module footprint, the power circuit can be broken down into single phases or even single functional switches. Compared to the traditional frame based module, the versatile and flexible molded modules can easily fit into restricted assembly space.

The molded power module shows significant mechanical robustness. The electrical isolation is created by the mold compound itself and does not require an additional soft-gel filling as is typical in frame based modules. Therefore significant pressure can be applied when the module is mounted and pressed into thermal interface material to allow for good thermal contact.

Due to their rugged design, molded power modules provide sufficient thermal cycle and lifetime capability to meet typical requirements of automotive traction applications.

An additional plus represents the package resistance to higher operating temperatures making it an ideal candidate for the use of SiC or GaN in future designs and junction temperatures up to 200ºC. However, further improvements in the bonding and joining technologies are required to take full advantage of this benefit.

The only drawback calling for special attention is the thermal stack. A molded power module is by design without a base plate and therefore without a heat spreader. This is an advantage in its life cycle capabilities for slow temperature cycles but it also increases the need for an efficient cooling approach.

Regardless of the chosen power module technology, a key to increased power density and integration is the use of liquid cooling. It has been demonstrated in numerous publications that advanced methodologies of liquid cooling allow for high thermal transfer coefficients.

A specific advantage can be obtained with an efficient ShowerPower® cooling system, substituting complex metal structures such as pin-fin base plates with simple and inexpensive plastic turbolaters [15-17]. Figure 3 shows an assembly of molded power modules mounted on a ShowerPower® cooler.

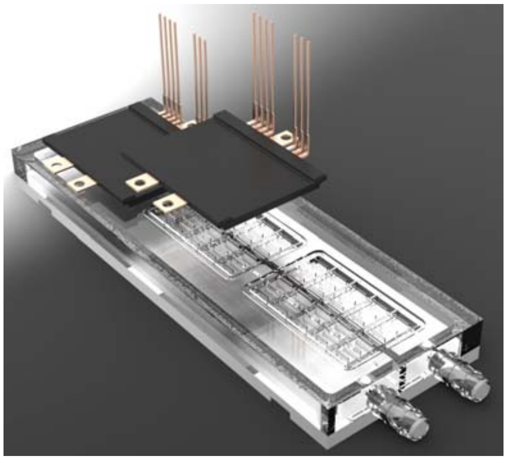

Figure 3. Mold-Module, direct liquid cooled underneath the DBC with highly efficient ShowerPower®-Turbulators.

4. Outlook in Packaging Technology

The increased demands in power density, cost and lifetime require new bonding and joining technologies. The soft solders used for die attach as well as substrate-to-baseplate attach in the current generation of power modules have become a bottleneck for the reliability demands of the automotive industry. The answer to this is the introduction of the low temperature silver sintering technology, which provides creep-free interconnects between chip and substrate as well as between substrate and baseplate; this will increase the lifetime of these joints [7].

But even the improved reliability of the semiconductor joints does not solve the aluminum bond wire lift-off problem.

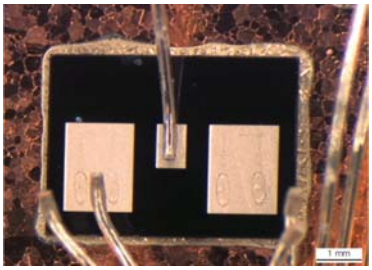

Figure 4: Bond wire lift off on power semiconductor after power cycling.

Due to the differences in coefficients of thermal expansion between the silicon chip and the aluminum bond wire every temperature change will induce stresses in the aluminum-silicon interface. Table 1 shows typical coefficients of thermal expansion (CTE).

Table 1. Thermal stack properties.

Material	Thickness [µm]	Thermal conductivity [W/(m K)]	CTE [ppm/K]
Al	125-500	220	24
Si	70-220	150	2-3
Solder	100	47	25
Cu	300	390	18
Al_2O_3	320	24	7
Cu	300	390	18
TIM	100	~1	N/A

The low cycle fatigue model by Coffin & Manson has successfully been used to assess the lifetime of the wire bond connection.

Figure 5, shows the relationship between the size of the temperature swings ΔT and the number of cycles to failure. It is seen that the larger the temperature swing the fewer cycles to a catastrophic wire bond lift off. The three data series represent three different average temperatures, Tm, at which the temperature cycling occurred. It is seen that the lower the average temperature the longer the life. In conclusion the chart shows that cooling is essential for achieving long lifetime. Not only will efficient cooling reduce the size of the temperature swings but also the average temperature at which they occur.

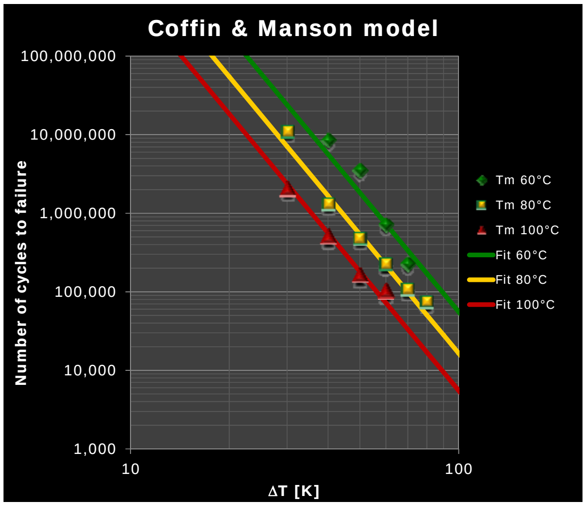

Figure 5. The Coffin & Manson diagram for wire bond fatigue. Better cooling will reduce the size of the temperature swings, ΔT, as well as the average temperature, Tm, thus increase the lifetime.

Since mission profiles for HEVs and EVs comprise hundreds of thousands to millions of temperature swings it is obvious that tremendous stresses are put on the bond-wire-semiconductor connections.

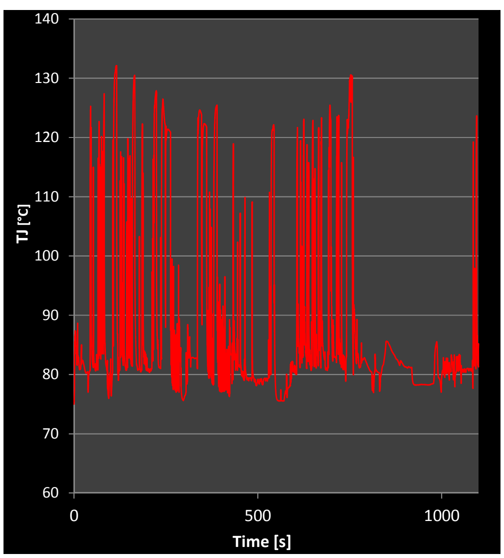

Figure 6. Part of a typical mission profile for a HEV, here 1100s (~20mins) of the profile is shown; it contains several large temperature swings.

The solution until now has been to increase the amount of silicon in the power modules, i.e. more semiconductors in parallel per switch, which reduces the thermal resistance which again leads to reduced temperature swings and consequently higher reliability. This leads to a substantial derating of the power modules of a factor of up to three meaning that three times more silicon is needed for the lifetime requirements than needed from a pure electrical perspective.

Research conducted at multiple power module manufacturers in conjunction with research institutes shows that the most likely solution is copper wire bonding on specifically prepared semiconductors. This, in combination with the low temperature silver sintering technology will offer the ultimate level of power density and reliability [1-7].

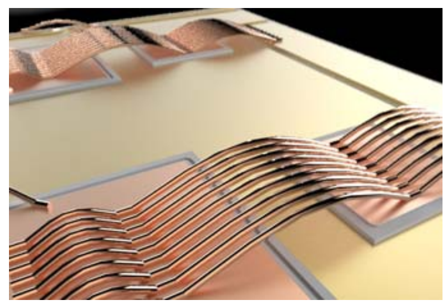

Figure 7. The ultimate power module: the power semiconductors are low temperature sintered onto the gold-plated DCB substrate. The top metallization of the semiconductors is compatible with the copper wire bonding process.

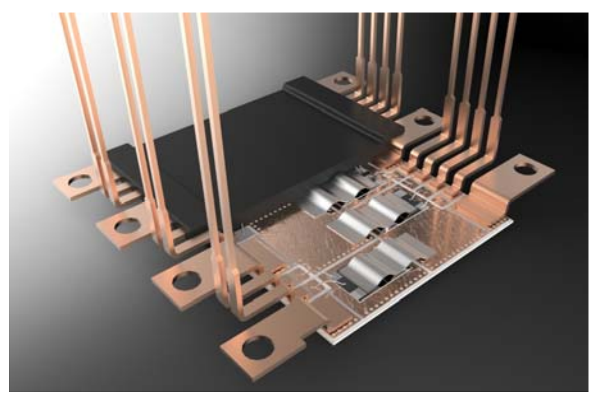

Figure 8. MOSFET-B-6 Bridge with Ribbon top-side interconnect.

5. Outlook in Cooling Technology

Liquid cooling is the state of the art cooling technology of power modules in HEVs and EVs. Due to space, weight, and performance constraints direct air cooling is totally out of the question. As an example consider the cooling area needed to dissipate 100W of excess heat for three different cooling technologies: standard natural convection air cooling, forced convection liquid cooling as used in today's HEVs and 2-phase cooling.

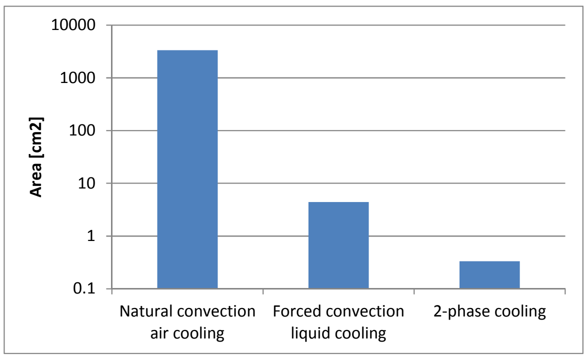

Figure 9. Cooling area needed to dissipate 100W.

As is seen in Figure 9 the cooling area needed is 1000 times higher when using air cooling compared to liquid cooling. Even an advanced folded fin cooler will take up a considerable volume compared to a liquid cooler which will make the air cooled solution unsuitable for HEV and EV applications. The chart further shows that by applying 2-phase cooling the cooling area required will be reduced even further with a factor of 10-20.

5.1 Single phase liquid cooling

There is a clear distinction between what is termed closed liquid coolers and open coolers; a closed cooler, or cold-plate, is basically a metal plate with integrated tubing; the power modules are then attached to the cold plate using a thermal interface material (TIM) See

Figure **10**.

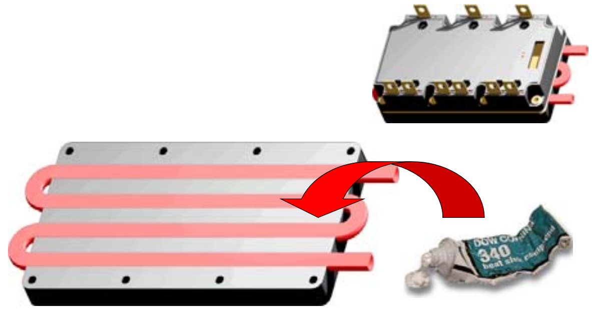

Figure 10. Cold plates for electronics cooling always require a thermal interface material, TIM.

Since the TIM represents a significant contribution to the thermal resistance from semiconductor junction to coolant, an improvement in cooling performance is obtained by eliminating the TIM layer and then directly cooling the backside of the power module. Direct liquid cooling may be realized by introducing pin fins in the module baseplate

Figure 11) or by using the ShowerPower® principle as seen in

Figure **12**.

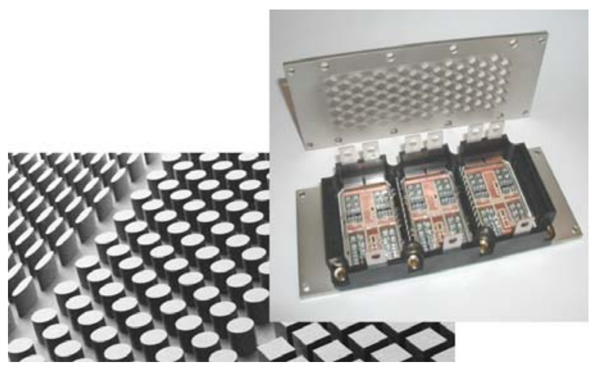

Figure 11. Pin fin cooler for a large IGBT traction power module; numerous pin designs are possible.

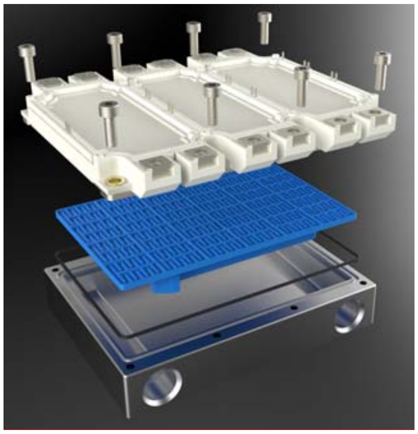

Figure 12. Eplus power module on a ShowerPower® cooler.

The key features of the ShowerPower® cooling concept is the high cooling efficiency, homogenous cooling across the power module, ensuring the same temperature of all semiconductors, and the ability to cool standard flat baseplate based power modules.

Using ethylene-glycol-water mixtures for power electronics cooling is standard practice in HEVs; either the cooler for the power electronics is hooked onto the cooling system for the combustion engine or a separate small cooling circuit is implemented especially for the power electronics. The latter option has the great advantage of a much lower coolant temperature (typically 60-75°C) compared to combustion engines cooler providing temperatures of 90-110°C. This temperature delta has significant impact on reliability and consequently on the de-rating factor - cost.

5.2 Two-phase liquid cooling

As indicated in Figure 9, 2-phase cooling, will be the next leap forward in thermal management of power electronics. Since the heat removal capability by evaporating a fluid is orders of magnitude larger than simple convection cooling the area needed for cooling the modules are reduced dramatically and a similar reduction applies to the condenser area. Figure 13 shows two alternative two-phase cooling concepts for power modules.

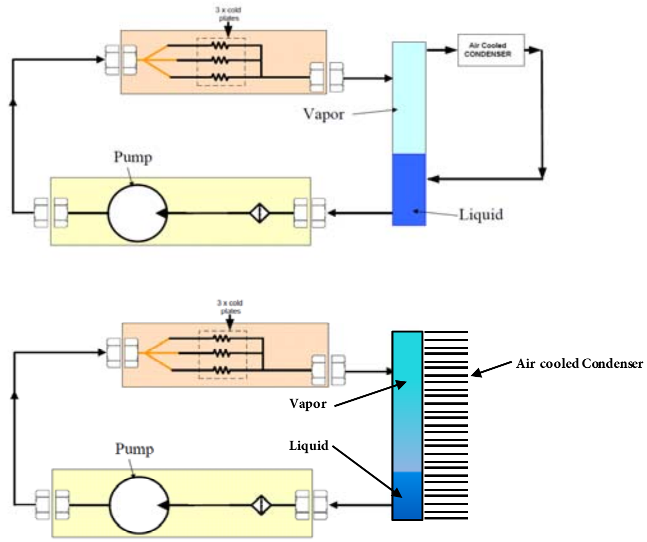

Figure 13. Two-Phase-Cooling concept for Power Modules.

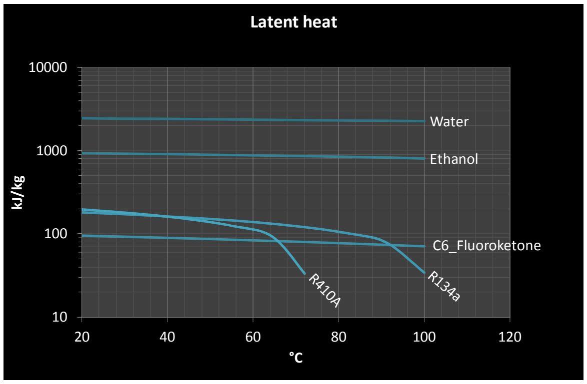

Figure 14. The heat of evaporation, latent heat, for various refrigerants.

Figure 14 can be used to assess the mass flow rate needed in a two phase cooling system for power electronics. The typical heat loss from a 50kW inverter power module in a HEV is typically 0.5-1kW (1-2%). With a latent heat of 200J/s a mass flow of 2.5-5g/s R134a is needed.

6. The Next Dimension (Outlook)

The ShowerPower® cooling concept enables compact 3D designs. Utilizing the flexibility of the transfer molding technology the ShowerPower® principle can be integrated in the mold module enabling a true scalable design approach.

Figure 15. A family of stacked ShowerPower cooled transfer moulded power modules (Danfoss Silicon Power).

Coolant inlet and outlet is connected to the module stack at the top side, underside or a combination thereof.
The screen capture below shows the result of a CFD analysis (computational fluid dynamics) of a 6-module stack. Detailed analysis shows that it is possible to design a stacked ShowerPower® where all the power semiconductors are cooled equally well, which means that the homogenous cooling of the ShowerPower® principle is brought into the third dimension.

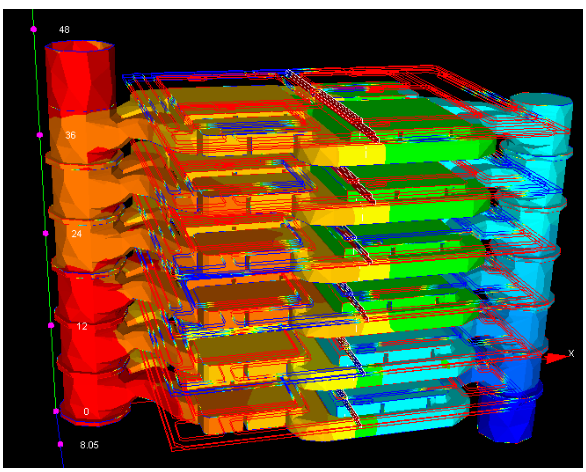

Figure 16. The coolant of a 6-module stacked ShowerPower assembly. Colors indicate pressure, inlet is at the upper left and outlet at the lower right.

The transfer molded module shown in the figures is a 300A 600V half bridge IGBT module, thus three modules comprise a three phase inverter module. Six modules would make up a 600A 600V inverter module and so on. The approximate volume for the 3-module-cooler assembly is 200cm^3.

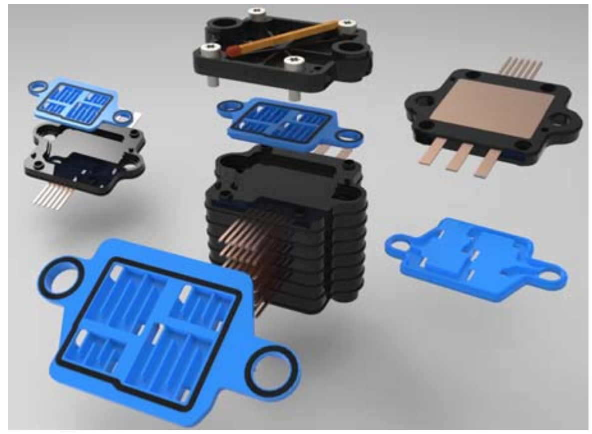

Figure 17. Stacked ShowerPower®, exploded view and details of the single elements (Danfoss Silicon Power).

The concept also allows for using standard transfer mold modules as seen in the picture below.

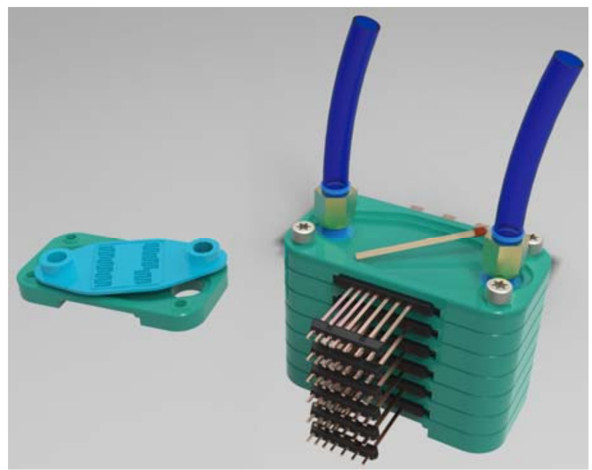

Figure 18. Stacked ShowerPower® using standard transfer molded modules (Danfoss Silicon Power).

6.1 Higher levels of integration

Further room for improvements in efficiency, power density and cost are possible by taking a more holistic, systems approach. Bringing multiple development partners together offers the opportunity to custom design systems with the highest level of efficiency for a particular application. Figure 19 shows an integrated design of film capacitors, busbar and molded power modules, utilizing a double-sided ShowerPower® liquid cooler to cool power modules and busbar simultaneously.

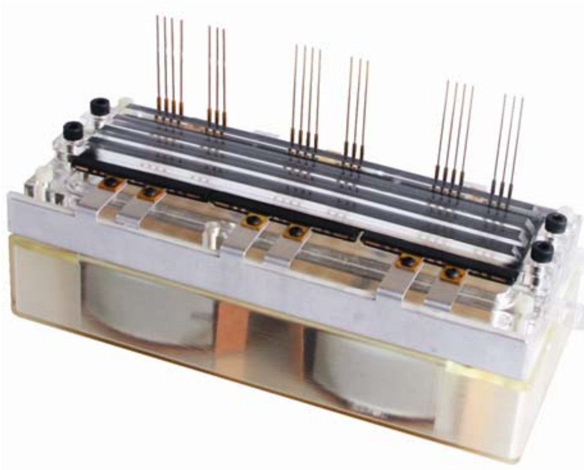

Figure 19. 80kW Inverter demonstrator with integrated double-sided ShowerPower® cooler, efficient busbar structure, film capacitors and standard transfer molded modules (Danfoss Silicon Power, SBE, Methode).

By definition a pure electric vehicle does not have a combustion engine and the associated cooler is of course absent too. Introducing a liquid cooling system for the power electronics only would then be something extra to make room for under the hood.

Due to cabin comfort requirements it would be unthinkable for the automotive industry to try to market EVs without an air-conditioning system. Danfoss research activities focus on integrating the thermal management systems for the power electronics, the batteries, and the electric motor into the already existing air-conditioning system. This will not only simplify the architecture of the EV as a whole but it will also increase the driving range of the EV by up to 30% compared to systems heating the cabin by use of electrical power from the batteries. The idea is to move energy around in the EV where it is needed, e.g. by using waste heat from the power electronics as cabin heating instead of using additional electric heating elements like in today's EVs.

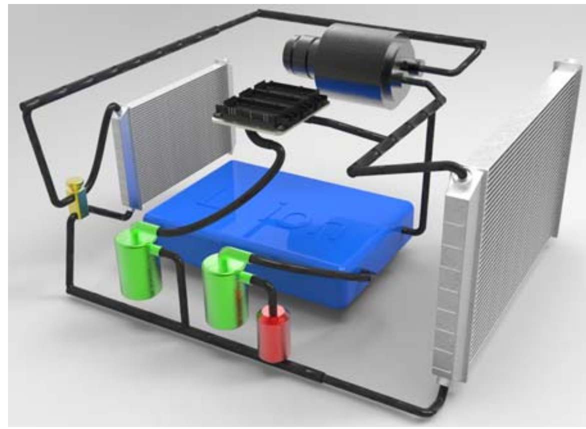

Figure 20. Total energy management system for an electric vehicle. The compressor (dark grey), evaporator, condenser and expansion valve (yellow) comprise the basic A/C system of the EV. The A/C system includes additionally two separate pumped cooling circuits, one for the power electronics (black) and one for the Li-ion battery (blue).

7. Summary

Significant improvements in power density and efficiency in automotive power electronics without jeopardizing lifetime or reliability are desired to assure long-term commercial viability of the EV and HEV market.

This paper identified the dynamic load profile of automotive traction applications as a major threat to power modules' life time. It shows that a system approach combining advanced packaging technologies including an improved thermal stack with efficient cooling technology provides the desired results in life time, power density and scalability for automotive traction inverters. It also shows that the technology has further potential through scalable 3D power module configurations and 2-phase liquid cooling.

It is unlikely that tomorrow's optimized solutions will be a "one-fits-all" design. Customized designs optimized for the application are likely required to maximize efficiency and meet the specific requirements. This will in turn require a closer relationship on a technical level between the partners involved. Close development cooperations offer further opportunities for higher level integrated solutions providing additional room for system optimization.

References

[1] “Thermal Design of Power Modules in Electrical Power Steering Applications”; R. Eisele, T. Senyildiz; ECPE-Seminar 2004, ABB, Zürich, CH

[2] ”Low Temperature Joining Technique for Better Reliability of Power Electronic Modules”; J. Rudzki, R. Eisele; 2007; Microtherm 2007; Lodz, Poland

[3] “Low temperature joining technology; a high reliability alternative to solder contacts”; U. Scheuermann, P. Wiedl; Workshop on Metal Ceramic Composites for Functional Applications, Vienna 4./5. June 1997

[4] „Neue .XT-Technologie von Infineon erhöht deutlich die Lebensdauer von IGBT-Modulen und ermöglicht Sperrschicht-Temperaturen von bis zu 200 °C“; Pressemitteilung; Informationsnummer INFIMM201005.046

[5] BMBF – Project „WireCoat“, Entwicklung einer Prozesskette für die Herstellung, die Verarbeitung und den Einsatz von beschichteten Bonddrähten; 2006-2009.

[6] “Pressure Sintering for Thermal Stack Assembly”;
R. Eisele, J. Rudzki, M. Kock; PCIM 2007, Nuremberg

[7] J. Rudzki, R. Eisele, Reliability of Ag Sintering vs. Soldering, ECPE Workshop Paris 2009

[8] “Substrate Free Molded Power Module“; F. Osterwald, M. Kock, T. Nagel, T. Senyildiz, R. Eisele; PCIM 2009 , Nuremberg

[9] “Neues Packaging für kundenspezifische Leistungsmodule“; R. Eisele, F. Osterwald; KLSH Seminar 2010, http://www.kompetenzzentrum-leistungselektronik.com/

[10 “Power under the hood - Increasing power density of inverters with a novel 3D-approach”; K. Olesen, R. Bredtmann, R. Eisele, F. Osterwald; APE-Automotive Power Electronics" International Conference SIA, Paris, 2010

[11] "Power Control Unit for High Power Hybrid System"; H. Yasui, H. Ishiyama, M. Inagaki, K. Mamitsu;
Denso Corporation; T. Kikuchi; Toyota Motor Corporation; 2008

[12] Newsletter des FhG-IZM; SDI; 01/2011

[13] “Review on Highly Integrated Solutions for Power Electronic Devices”; J. Schulz-Harder, Electrovac Curamik

[14] “Thermisches Management auf Bauelemente-Level”; M. Poech; 2008; Seminarunterlagen Fraunhofer Institut für Silizium Technologie, Itzehoe

[15] „Innovative Kühltechnologie für Leistungshalbleitermodule; R. Eisele, K. Olesen, F. Osterwald, ETG-Fachtagung, Bad Nauheim, 2006

[16] ”ShowerPower® New Cooling Concept”, K. Olesen et al.; PCIM 2004, Nuremberg

[17] ”ShowerPower® New Cooling Concept for Automotive Applications”, K. Olesen et al.; APE, June 21-22 2006, Paris

[18] “Cooling of IGBT Modules with Vaporizable Dielectric Fluid (VDF)”; D. Levett, J. Howes, D. Saums; IMAPS France Advanced Technology Workshop on Thermal Management 2008, La Rochelle, France 30-31 January 2008

[19] “EVALUATION OF THE 2010 TOYOTA PRIUS HYBRID SYNERGY DRIVE SYSTEM”; Mitch Olszewski, Program Manager; Oak Ridge National Laboratory 2011, U.S. Department of Energy Vehicle Technologies, EE-2G

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