Towards an Integrated Drive for Hybrid Traction

Martin Maerz[1)], Ernst Schimanek[2)], Markus Billmann[1)]

[1)] Fraunhofer Institute of Integrated Systems and Device Technology (IISB)
Schottkystrasse 10, 91058 Erlangen, Germany
Tel. (+49) 9131 / 761 311, e-mail: martin.maerz@iisb.fraunhofer.de

[2)] Consulting Engineers E. Schimanek
Landgrabenstrasse 94, 90443 Nuremberg, Germany
Tel. (+49) 911 / 235 68 28, e-mail: ernst.schimanek@t-online.de

Abstract - This paper describes the motivation for inverter integrated drives for hybrid traction and gives an overview of the technical requirements that must be fulfilled by corresponding systems in the automotive powertrain. At the example of a first prototype system, a 3D integration technique for the power electronics is presented. This technique provides an effective cooling for all active and passive components. A very high power density can be achieved this way.

1. Introduction

Hybrid traction, i.e. the combination of a combustion engine and an electrical machine, is the most promising approach to reach the ambitious vehicle emission reduction targets, such as the ACEA agreement[1]. Successful series cars, like the Toyota Prius or the Honda Civic IMA, confirm the fuel consumption reduction potential of this technique - especially under city traffic conditions. Awards such as "US Car of the Year 2003" or the no.1 in ADAC Eco-Test (both Prius II) result in enormous publicity and increasing customer demand.

The aim of hybrid drives is to combine the advantages of two sources for traction power most efficiently in order to get the best performance with respect to fuel consumption, low emission, vehicle dynamic, comfort, etc.

The history of hybrid traction vehicles started in 1900, when the “K.u.K. Hofwagen-Fabrik J. Lohner & Co.” from Vienna presented the first electric driven vehicle at the World Exhibition in Paris. The vehicle, developed by a young and at this time still unknown engineer named Ferdinand Porsche, was equipped with two wheel hub motors, each with a power of 7hp. The battery with a capacity of 300Ah, a voltage of 80V and a weight of 410kg allowed a cruising range of about 50km. Porsche later supplemented a 16hp Austro-Daimler gasoline engine to charge the battery and thus created the first hybrid traction system, which he called “Mixte Drive“ (s. Fig. 1).

Nearly a century later, the hybrid traction approach is experiencing a renaissance. Beside the increasing interest in fuel consumption reduction this development is also boosted by new technical possibilities with modern power electronics. In the last years, virtually each automobile manufacturer has started great efforts in the direction of hybrid traction systems.

Today’s most popular and successful hybrid vehicle is the Toyota Prius. Toyota introduced the first generation of the Prius in 1997, since 2003 the second generation of this car is available. Within the Prius two electric machines and a special gear box for torque distribution form a highly integrated electromechanical system. One electric motor is for traction another for electrical power generation. The electronic system which comprises all the power and control electronics is housed in a separate water-cooled box (s. Fig. 2). This box is placed in the engine compartment beside the combustion engine. A separate cooling water cycle with a lower inlet temperature is available. The interconnections between motor, electronics and battery are made by several cables [1].

The Prius is designed around the hybrid powertrain. If one thinks about a hybrid drive as an upgrade option for conventional cars, one must consider that in modern cars the size and weight of components becomes an increasingly serious problem. More and more components are built e.g. in the engine compartment. Thus a very compact design and a high power density of all components is absolutely

***Fig. 1:** The first hybrid vehicle »Lohner Porsche« 1900*

[1] The European Automotive Industry (ACEA) has commited a reduction of the CO_2 emission to 140g/km in 2008. The EC is targeting 90g/km till 2020.

Fig. 2: *Power control unit of the Toyota Prius II (top); combustion engine with the gear-box and the electric machines (bottom) (Source: Toyota)*

necessary. In this context, even components like cables or connectors, e.g. between a motor and the electronics, can become a serious problem.

Beside the system size cost reasons favour an integration as well, because expensive components like a separate housing for the inverter, shielded cables and high-voltage connectors can be omitted. And last but not least EMC/EMI is easier to handle when motor and inverter are integrated into a common metal housing.

Therefore the target must be a mechatronic integration of the inverter and the electric motor. Mechatronics means the most effective integration of mechanics, power electronics, sensory and controls in one functional unit. The challenge is that this integration must be effective not only with respect to system size, but also with respect to costs, functionality, manufacturability, testability and reliability.

2. Requirements on Integrated Drives for the Automotive Powertrain

Hybrid vehicles are classified as mild hybrids (5-20kW), full hybrids (20-60kW) or power hybrids (>60kW) in terms of the contribution of the electrical drive system to the total traction power. In brackets a rough estimation of the corresponding power range of the electric drive system is given.

With the exception of mild hybrids in the lower power range, water cooling is necessary for the electric motor and the power electronics. This is due to the high power dissipation – even with highly efficient components – and the high ambient temperature near the combustion engine.

Because of size and cost reasons, future hybrid vehicles should have only one single water-cooling cycle for all components – the combustion engine, the electric motor, and the power electronics.

Modern combustion engines operate with a coolant temperature of up to 105°C for efficiency reasons. This temperature also applies to the electronics – not as a short term stress but for normal operation. Under special operating conditions (e.g. coasting of temperature) the coolant temperature can rise up to 120°C. Even if no output power is required from the power electronics in this case, no damage may occur. The ambient temperature in the engine compartment can rise up to 125°C – close to the combustion engine up to 140°C. All components have to be designed for these temperatures.

When talking about the lifetime of automobiles, one must distinguish between the active service life and the passive life. The later is estimated about 15 years while the active service life lasts about 10.000h, corresponding to a mileage of about 300.000km.

The active life is generally split in several phases, e.g.:

- ❑ Coolant temperature < 90°C for 95% of the active service life
- ❑ Coolant temperature > 90°C for 5% of the active service life (max. 30 minutes en-bloc)

Assuming a lifetime of about 15 years and two cold starts per day, meaning the coolant is heated up twice from 5°C to 105°C and cooled down again, all components involved have to sustain 11.000 passive temperature-cycles with a shift of 100K over their product life. In addition to this, active temperature cycles stress the components. The amplitude of the active cycles is a function of the time depending power dissipation (corresponding to the mission profile), the cooling conditions (thermal resistance) and the thermal time-constant of each component.

The windings of the electric machine for example heat-up to an average temperature that is considerably higher than the coolant temperature. Modern insulation systems allow temperatures up to 200°C. Due to the large thermal time-constant of an electric motor, one can calculate with about 100.000 cycles with a temperature amplitude of 20-30K during a vehicle lifetime. The situation is quite different for the semiconductors and their direct environment (bond wires, substrates, etc.), where the thermal time constant is in a range of some milliseconds to a few seconds. Each acceleration and braking of the vehicle results in a temperature change. One must reckon with a much larger number of temperature cycles therefore - approximately 3.000.000 with an amplitude of 30K.

It is obvious that under such operating conditions, system design for reliability is one of the essential subjects.

Another great challenge with a mechatronic integration is the complex structure of the volume available for the electronics. This volume is generally predefined by the mechanical requirements and not by the requirements of the power electronics.

In case of an inverter motor there normally is a ring-shaped volume around the electric machine to be used, but this volume is often additionally cleaved by studs and ribs. The structural conditions are therefore not comparable to conventional electronics. This requires new approaches for a 3D integration of power electronics and new kinds of components with a higher structural flexibility.

3. General Design Considerations

Fig. 3 shows two basic concepts how to integrate power electronics into an electric machine. The left-hand side variant uses the ring-shaped area on the face of the stator iron stack directly beside the stator winding. The design variant on the right makes use of the ring-shaped volume radially outside the stator iron stack.

The integration on the face of the stator allows a larger diameter of the machine and with that a higher torque. However, since the electronics is very close to the hot stator windings, a sophisticated thermal shielding technique is necessary in this case. The thermal decoupling between motor and electronics is much easier if the water-cooling jacket is placed between the motor and the electronics as in the design variant on the right.

An absolute prerequisite for achieving a high power density and high system reliability is that also the passive power components are included in the thermal system design. Passive components generally consist of materials showing a poor thermal conductivity like polymers (capacitors), iron powders or ferrites - thus large heat conducting areas and short heat paths are necessary for effective cooling.

An essential criteria for the thermal system design is the heat flux density produced by the individual component and the temperature headroom. This is the difference between the maximum operating temperature of the component and the maximum coolant temperature. The higher the heat flux density and as lower the temperature headroom the tighter the thermal coupling to the heatsink – e.g. the water-cooling jacket – must be. Typical heat flux densities are in the range of 50...500W/cm^2 for power semiconductor devices, 0.1...3W/cm^2 for magnetic components and below 0.1W/cm^2 for capacitors.

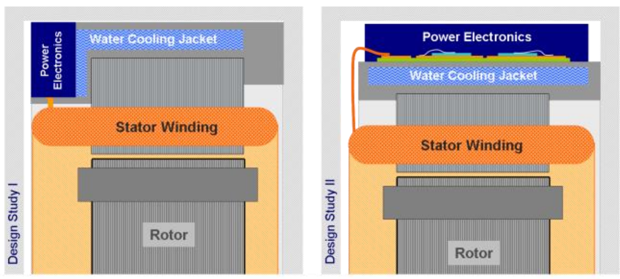

Fig. 3: *Two design studies how to integrate an inverter into an electric machine*

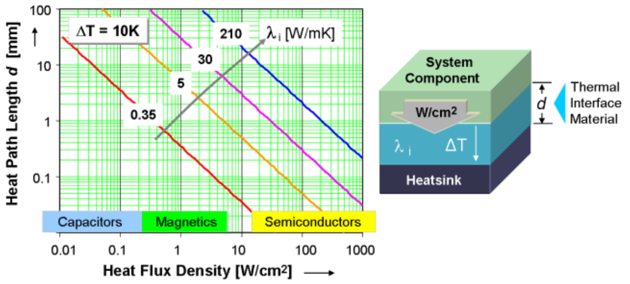

Fig. 4: *Possible thickness of a heat conducting layer depending on heat flux density and thermal conductivity*

The diagram in Fig. 4 gives the possible heat path length depending on the heat flux density for various thermal conductivities of the interface material, under the assumption of a temperature difference of 10K across the interface layer. This diagram is also valid in the case of volume heating, if the permissible heat path length is doubled with single-sided cooling and quadrupled with double-sided cooling [4]. A single-sided cooled dc-link foil stack capacitor is to be exemplary considered under the following assumptions: volume heating, heat flux density at the cooled surface 0.05W/cm^2, specific thermal conductivity of the foil λ = 0.35W/m·K, temperature drop across the capacitor 10K. For this case one can read from Fig. 4 that a height of the foil stack of about 15mm is possible - an absolutely practical useable value.

As an example, Fig. 5 shows two cross-sections through an integrated inverter motor with the power electronics placed on the face of the stator. The power semiconductors are mounted on ceramic substrates. The substrates are soldered on a base-plate, which is directly water-cooled by the vehicle coolant. A heat shield, which is thermally coupled to the coolant, limits the heat-flow from the hot windings, and allows to limit the ambient temperature in the power electronics area to 125°C. The ends of the stator windings are directly attached to the DCB of the power modules in order to prevent a carry-over of heat into the current sensors and the inverter.

Due to the high ambient air temperature, even low heat flux density components like the dc-link capacitors, the

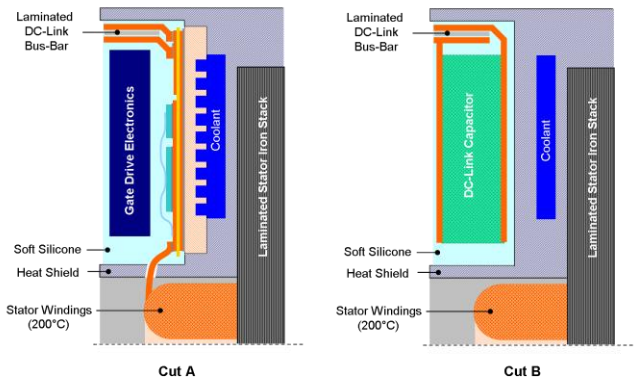

Fig. 5: *Simplified cross section through the integrated inverter shown in Fig.8 at two different cutting planes*

gate drive electronics and the DC-link bus-bars must be thermally coupled to the coolant, e.g. via a soft silicone compound that fills the entire inverter volume. The sealing not only ensures protection against contamination and humidity in this case, but also provides a much more homogeneous temperature distribution and thus greatly improves the thermal situation within the power electronics.

With respect to a high system reliability special care must be taken on any connection between materials with different coefficients of thermal expansion (CTE). The temperature cycling during operation causes mechanical stress that fatigues the interconnections. The material stack between the power semiconductors and the coolant, which comprises the power chips, solder, copper layers, the ceramic substrate and the base-plate is one of the most critical laminates. By means of proper material choice and constructive measures the thermo-mechanical stress must be minimized.

4. Towards an Integrated Inverter Drive

Fig. 6 shows an inverter motor for hybrid traction, developed in cooperation with DaimlerChrysler [2]. In contrast to previous solutions the inverter is not simply attached to the electric machine, but mechatronically integrated into the motor. This demonstrator was realized by introducing some innovative solutions and novel technologies:

- ❑ Curved power electronic modules with integrated current sensors and direct liquid cooling
- ❑ Metallized film capacitor bricks with high ripple current rating and high operating temperature for the dc-link (Power Capacitor Chips (PCC) in MKK technology from EPCOS)
- ❑ Circular shaped laminated dc-link bus-bar
- ❑ Sophisticated thermal management techniques for the power electronics
- ❑ Isolating gate driver with high EMI noise immunity and high operating temperature [3].

The inverter is designed ring-shaped (inner diameter 312 mm, outer diameter 404mm) and can be directly inserted in the stator housing. The cross sectional views through the power electronics correspond to the illustrations in Fig. 5. With a dc-link voltage of 400V, the inverter is capable to handle an apparent power of 90kVA, resulting in an output power of the induction machine of about 45kW. The total height of the inverter is 3cm, which gives an inverter volume of about 1.5dm^3 and a power density of 30W/cm^3 (i.e. 490 W/in^3).

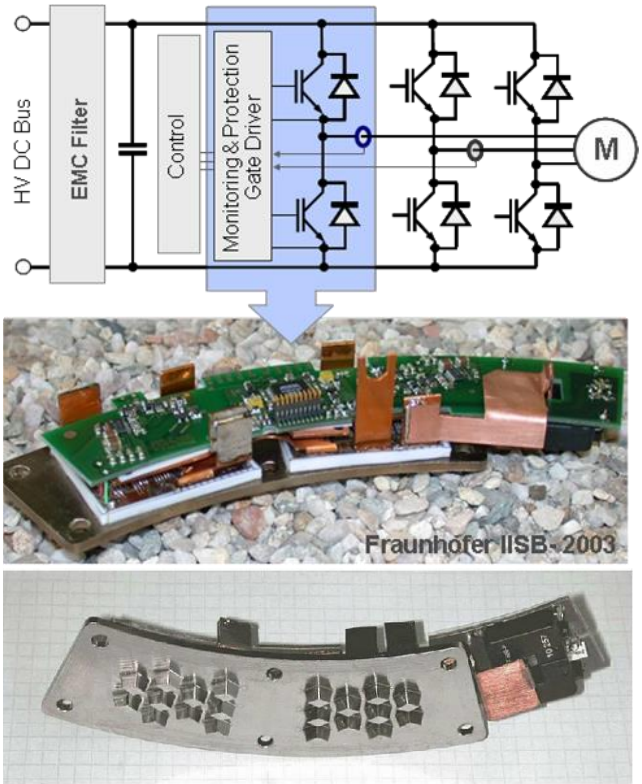

Fig. 7: Intelligent power module with integrated current sensor and direct liquid cooling (IGBT: 600V, 300A)

Fig. 7 allows a detailed view on the application specific intelligent power module (IPM), which was developed for this integrated drive. Three of these modules form the heart of the inverter. Each module realizes an IGBT half-bridge comprising two 600V/300A IGBT-switches with the corresponding freewheeling diodes. The gate drivers are galvanically insulating and offer extensive protection and diagnosis functions. A consistent renunciation on temperature sensitive components, like opto devices or electrolytic

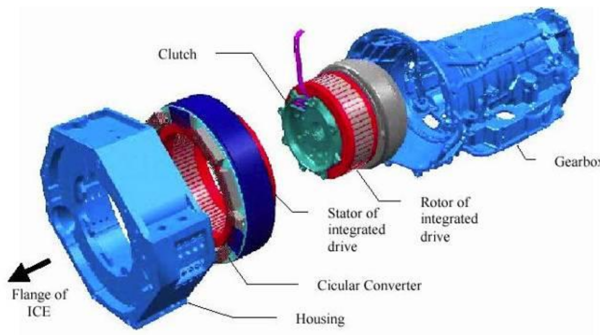

***Fig. 6:** Integrated inverter motor for a hybrid car in P2 configuration [2]*

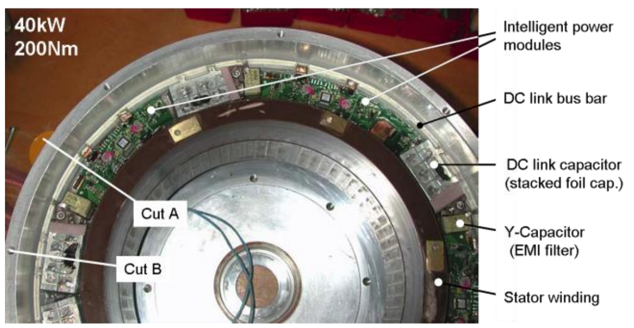

***Fig. 8:** The stator of the induction machine with integrated inverter.*

capacitors, allows a stable operation under the given high-temperature conditions. Fig. 8 shows a photo of the stator with the housing and the integrated inverter.

5. Conclusions

The 3D mechatronic integration of an inverter into an electric machine for hybrid traction requires a multi-disciplinary cooperation of experts from power electronics, mechanics, production techniques and material science. A lot of R&D work is still necessary to fulfill the ambitious cost and reliability targets. In front of this background, the ECPE demonstrator program has been started.

6. Acknowledgment

The authors would like to thank the state of Bavaria for supporting this work in the framework of the mechatronics research program (BKM).

7. References

[1] Tadano H., TOYOTA Central Research and Development Laboratory: *Power Devices and Systems in Automobile*, CIPS, June 20-21, 2000

[2] Tadros Y., Ranneberg J., Schäfer U.: *Ring Shaped Motor-Integrated Electric Drive for Hybrid Electric Vehicles*, EPE 2003, Toulouse

[3] Zeltner H., Maerz M., Billmann M., Schimanek E.: *A compact IGBT driver for high temperature applications.* PCIM Conference Proceedings, Nuremberg, 2003

[4] Maerz M.: *Thermal management in high-density power converters.* IEEE ICIT Conference, Maribor, 2003