Mechatronic Integration into the Hybrid Powertrain
– The Thermal Challenge

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Abstract - This paper gives an overview on the requirements and challenges with the integration of a high power drive inverter into the automotive drive-train. Harsh thermal and mechanical constraints require new approaches for a 3D system integration, new materials, and new components for the power electronics. A prototype system of an electrical drive unit for hybrid traction is presented that provides unique power density and fits into an existing drivetrain.

1. Introduction

The aim of hybrid drives is to combine the specific advantages of two different sources for traction power most efficiently in order to get the best performance with respect to fuel consumption, low emissions, vehicle dynamics, driving fun and comfort.

Today, the term „hybrid“ is generally used as a synonym for the combination of a combustion engine and an electric machine. This concept is the most promising approach to reach the ambitious vehicle emission reduction targets, such as the ACEA agreement\textsuperscript{1}. The potential of this technique with respect to fuel consumption reduction, especially under city traffic conditions, is widely confirmed by successful series cars like the Toyota Prius, the Lexus RX400h or the Honda Civic IMA, as well as by numerous experimental cars.

The time is ripe for hybrids - now! Awards such as “US Car of the Year 2003” or the no.1 in ADAC Eco-Test (both Prius II) resulted in enormous publicity and increasing customer demand. Meanwhile, already more than 500,000 hybrid vehicles are on the roads worldwide. The demand for hybrids is boosted by the continuously increasing fuel costs, but initial costs as well have become competitive through advances in power electronics and electrical energy storage technologies. In view of the facts, virtually each automobile manufacturer has started great efforts in the direction of hybrid traction systems in the last years.

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. The hybrid electronic system which comprises all the power and control electronics is housed in a single water-cooled box (s. Fig. 1). This quite bulky box is placed in the engine compartment beside the combustion engine. A separate water cycle provides a moderate coolant temperature for the electronics. The interconnections between the gear box, the electronics box and the traction 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 today’s cars the size and weight of components become an increasingly serious problem. In modern vehicles, not only the engine compartment, but nearly any available corner is already occupied by system components. A very compact design, i.e. a high power density, is therefore an absolute prerequisite for all new power electronics systems. In this context, even parts like cables or connectors, e.g. between a motor and the electronics, may cause difficulties.

Beside the package volume, 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 is easier to handle when motor and inverter are integrated into a common metal housing. Thus, a mechatronic integration of the inverter and the electric motor must be the target to fit the requirements of future vehicles.

\textsuperscript{1} The European Automotive Industry (ACEA) has committed a reduction of the CO\textsubscript{2} emission to 140g/km in 2008. The EC is targeting 90g/km till 2020.
2. Requirements on Inverter Drives in the Automotive Powertrain

Hybrid vehicles are classified as micro/mini hybrids (<10 kW), mild hybrids (10-25 kW), full hybrids (30-60 kW) or power hybrids (>60 kW) 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 micro/mini hybrids and 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 internal combustion engine (ICE).

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, an increase up to 115°C is requested for ICE efficiency reasons. This temperature also applies to any water-cooled 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, damage may not 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 about 100K over their product life.

Superimposed on these coolant temperature cycles are active temperature cycles (s. Fig. 2). The distribution of the amplitudes of the active cycles is a function of the time-dependent power dissipation in each component, the heating by neighbouring components (both corresponding to the mission profile), the cooling conditions (thermal resistance), and the individual 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 constants are 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 30...40K. It is obvious that under such operating conditions, system design for reliability is an essential subject.

Another great challenge of a mechatronic integration is the complex structure of the package volume available for the electronics. This volume is generally predefined by the mechanical requirements and not by the requirements of the power electronics. In the case of an inverter motor there normally is only a ring-shaped volume around the electric machine to be used for the integration, and - to make matters worse - this volume is often additionally cleft by studs and ribs. The structural conditions are therefore not comparable to conventional electronics. New approaches for a 3D integration of power electronics and new kinds of components with a higher structural flexibility are prerequisites to meet the given challenges. This especially applies to all large volume passive components like the dc-link capacitor and the EMC filter components (Fig.3).

3. General Design Considerations

Fig. 4 shows two basic concepts how to integrate power electronics into an electric machine. The left-hand side solution uses the ring-shaped area on the face of the stator iron stack directly beside the stator windings. The design on the right makes use of the ring-shaped volume radially outside the stator iron stack.

The integration on the face of the stator generally allows a larger diameter of the machine and with that a higher torque. This design has been used in the first generation of our integrated electric drive units for hybrid traction [2]. Since the power electronics is very close to the hot stator winding in this case, a sophisticated thermal shielding technique is necessary. A separation of the cooling jacket in two series-connected channels is quite simple with this arrangement. If the cooling channel for the power electronics is connected to the coolant inlet, the temperature level of the electronics can be reduced by about 10K. This is because in the power range typical for full hybrids (30...60kW), the total power dissipation in the electric drive unit (power electronics plus electric motor) can increase the coolant temperature by up to about 15K, assuming a typical coolant flow rate of 8 liter/min.

A thermal decoupling between motor and electronics with respect to radiated and conducted heat is easier if the water-cooling jacket is placed between the motor and the electronics as shown on the right hand side of Fig. 4. However, the electronics is exposed to the full temperature gradient between the coolant inlet and outlet in this case.

An absolute prerequisite for achieving high power density and a high system reliability is that not only the power semiconductors, but all components are included in the thermal system design. Many of the inverter components (like capacitors, inductors, PCBs, etc.) are made of materials with poor thermal conductivity and therefore require special attention.
Two of the essential criteria for the thermal system design are the heat flux density and the temperature headroom. The later means the difference between the maximum operating temperature of the component and the maximum coolant temperature. The higher the heat flux density produced by the individual component and the lower the temperature headroom, the tighter must be the thermal coupling to the heatsink, e.g. the water-cooling jacket. Typical heat flux densities lie in the range of 50...200 W/cm² for power semiconductors, 0.1...3W/cm² for magnetic components and below 0.1W/cm² for capacitors [3].

For each inverter component the mechanical design must ensure proper heat conducting paths. The design parameters in this context are the heat conducting cross-section, the heat path length, and the heat path material. Sealing materials, like e.g. soft silicone compounds, not only ensure protection against contamination and vibration, but can also provide a more homogeneous temperature distribution and thus greatly improve the thermal situation within the power electronics.

4. Towards an Integrated Inverter Drive

Fig. 5 shows the stator of the first generation drive system with integrated power electronics. An induction machine with a standard three-phase winding was used [2]. The large winding overhang gave space for the electronics, but also reduced the active motor length. The electrical drive unit was integrated into a housing to be mounted between the internal combustion engine (ICE) and the gear-box, and thus increased the total length of the drivetrain.

For the second generation system there was a strong request for a solution that completely fits into the existing drivetrain of a passenger car. The clutch-box was designated as the housing, in which an electrical drive unit with a mechanical output power of 50kW and a maximum torque of 220Nm had to be integrated, together with the complete inverter according to Fig.3. But the conical, tuba-shaped housing with internal studs and ribs considerably complicated the integration challenges.

The basic internal arrangement of the components is shown in Fig. 4 (right) and Fig. 6. A permanent magnet excited synchronous machine (PM machine) provides a very high power density and a high efficiency even in the low speed range. By using a whole-coiled winding (single teeth coils), the winding overhang could be greatly reduced, resulting in an increased active motor length. The torque disadvantage, caused by the conical housing and the thereby restricted motor diameter, could be equalized this way. The electrical circuitry of the motor windings corresponds to that of a classical three phase machine. Thus only three power interconnections between motor and inverter are necessary. Multi-functional winding interconnections prevent a heat transfer out of the hot windings into the power electronics.

In order to achieve an optimum usage of the available package volume, a ring-shaped dc-link capacitor has been developed in cooperation with the Epcos AG. This capacitor provides a capacitance of 500µF (450V). Its concentric, nearly coaxial terminals form the dc-link bus-bar and allow the realization of a very low parasitic dc-link. The ripple current rating of this capacitor is several hundred amperes and thus far beyond the actual ripple current load. The self-heating, caused by the inverter ripple current, is therefore negligible. However, in order to protect the capacitor against the high ambient temperature of up to 140°C, it is thermally coupled to the cooling jacket.
As can be seen from Fig. 6, three half-bridge power modules are placed at the periphery of the water cooling jacket that surrounds the whole electric machine. The remaining sections at the periphery are used for the control board, the current sensors and the EMC filter. Since the system is also intended as a test platform for different power module designs, special attention has been put on a modular and assembly friendly construction.

Fig. 7 shows an exploded view on the first application specific smart power half-bridge module. The power semiconductors are mounted on an AlN DCB substrate that is soldered on a directly water-cooled base-plate. Equipped with 600V-IGBT chips from Infineon, each module is able to control an AC current of 320A_{RMS} at a switching frequency of 8kHz, a coolant temperature of 115°C, and a DC-link voltage of 450V.

The gate drivers are galvanically insulating and offer extensive protection and diagnosis functions. Placed within the power module, only 2mm above the IGBT bond wires, the gate drive electronics is exposed to very hard thermal and electromagnetic operating conditions. With the driver concept described in [4], a very stable and safe operation of the power modules could be ensured. A prerequisite for a reliable operation under the given high-temperature conditions is the consistent abandonment of temperature sensitive components, like opto devices or wet electrolytic capacitors.

Special attention has been payed to an optimized thermal design of the power modules. The inverter drive is inserted in the existing coolant cycle of the ICE. The available coolant flow is about 8 liter/min and the maximum allowable total pressure drop 200 mbar. An optimization of the back-side structure of the modules is necessary in order to minimize the thermal resistance between the power semiconductors and the coolant, but not to exceed the maximum allowable coolant pressure drop. The cooling efficiency of a finger-structure varies with its geometry - namely the finger thickness, shape, height and surface - as well as the spacing and arrangement of the fingers. This optimization (s. Fig. 8) was realized with the 3D computational fluid dynamics software Flotherm™. An important issue in this context is that the parameters of the coolant, especially the viscosity of the water-glycol mixture (to down on 50:50), greatly vary along with the temperature.

The realized power modules showed a specific thermal resistance junction-coolant (R_{j,c}) of 0.45Kcm^2/W at a coolant flow rate of 8 liter/min and a pressure drop of 60mbar, both of which were close to the predictions from simulation. With respect to the coolant flow, the three power modules are connected in series, thus the specification of a total pressure drop of 200 mbar was achieved.

The prototype was built on a machined Cu base plate. This, of course, is no solution for series production, partly because of cost issues, but mainly because of reliability issues of the DCB to base plate solder joint. Due to the passive temperature cycles to be sustained (ca. 11,000 cycles with a mean temperature swing of ca. 100 K), an AlSiC base plate could be a choice to reduce the thermal mismatch between base plate and DCB substrate to an acceptable low level at a small expense of thermal efficiency.

Power cycling is another reliability issue, which has been met by the thermal design efforts. At nominal operation, the junction temperature rise has been verified with approximately 40 K. The requirement of about 3,000,000 cycles is therefore within the order of magnitude of experimental results (s. Fig. 9).
The control board of the inverter (s. Fig. 10) comprises an IFX XC164 microcontroller, a CAN-Bus and a resolver interface, the auxiliary power supply, and additional signal conditioning circuits. The power supply is designed to meet the input voltage requirements of a 12V automotive power-net. In order to ensure a close thermal coupling to the coolant and with that highly efficient cooling, a semi-flex design has been chosen to perfectly fit the motor contour. An all SMT design allows to glue the control board on adequate flat surfaces of the cooling jacket. A semi-IMS substrate with superior thermal properties is formed this way.

A picture of the electric drive unit is given in Fig. 11. The maximum mechanical power of this unit is 50kW, the maximum torque 220Nm. With a total package volume of the inverter of 1.3dm³ and an apparent power of 100kVA, the power density of the electronics reaches 75kVA/dm³ (i.e. 1.1kVA/n³).

5. Conclusions

Simultaneous engineering (electrical, mechanical, thermal) is an imperative prerequisite for a mechatronic integration of power electronics. Consistently following this way, an inverter drive for hybrid traction could be integrated into the clutch-box of a passenger car, i.e. in an environment and package volume that had been considered as absolutely useless for high power electronics so far. 3D integration, new components and sophisticated thermal management solutions opened the way to a system with unique power density. The next steps aim on a further optimization of the system reliability, manufacturability, and modularity.

6. Acknowledgment

The development of the drive system has been funded by ECPE in the framework of the demonstrator program “System integrated drive for hybrid traction”. The authors would like to thank ECPE as well as the state of Bavaria for supporting this work.

7. References