

Perspectives of Inverter Integration in Vehicle Powertrains

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Abstract: This paper describes new approaches for integrating inverters into electrified powertrains. Conventional solutions are dominated by separated inverters and e-machines with extensive electric and cooling interfaces in between. Generally the e-machine is combined or integrated in the gearbox. Consequently the integration of the power electronics into this package is the next step to achieve a highly integrated mechatronic module. Two specific solutions will be introduced: one solution for hybrid traction application with a double inverter and one solution for an electric-driven axle e.g. for a fully electric or fuel cell vehicle.

Keywords: Electric Axles, Double Inverter, Fuel cell Vehicle, Hybrid Powertrain

1. Introduction

State-of-the-art electric drives for traction applications have separate components. On the market established solutions are the hybridisations of vehicles e.g. Toyota Prius [1]. From the vehicle integration point of view the optimal solution is to minimize the interfaces respectively the cables and fluid pipes. The target is to bring the inverter as close as possible to the windings of the e-machine. Figure 1 shows a scheme for such integration scenario.

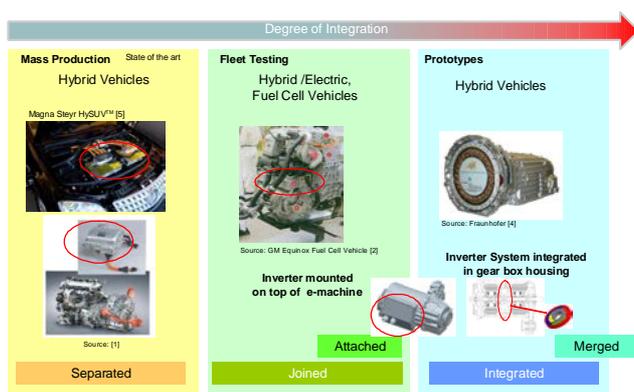


Figure 1: Inverter integration steps

The degree of inverter integration respectively the roadmap is determined from the specific requirements and different topologies of powertrain electrification. The highest integrated package “merged” – in best cases as volume neutral - is not automatically the optimal approach. The package modularity, ser-

viceability, thermal conditions, and costs for the module are parameters to find the best trade off.

On top mounted inverter will be the short term cost effective solution for launching into the market especially for vehicles with electric primary drive (battery electric vehicles, fuel cell vehicles, range extender vehicles). Recently there are a lot of demonstrator vehicles for fleet testing e.g. fuel cell application [2]. Prototypes and aspects for highly integrated inverters are discussed e.g. in [3] and [4].

2. Application 1: ICE Hybrid Powertrain

2.1 Requirements

The integration study is based on the hybridisation of the powertrain of a Daimler M-class vehicle which is achieved via a special designed electric 4WD traction module [3]. This module is located in the longitudinal drive train between the ICE and the automated manual transmission. Figure 2 shows the packaging situation realized as the classical separated topology. The module itself contains two electric machines (for parallel and for electric front axle) and in total four wet clutches installed inside the rotors. The corresponding two inverters are mounted on top of the ICE.

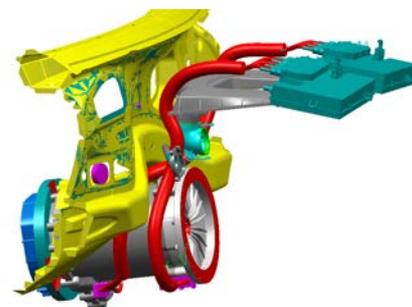


Figure 2: Typical separated inverter topology with two inverters

This concept is realized in the HySUV™ demonstrator vehicle from Magna Steyr. Following the integration roadmap the module has to contain both inverters with the same traction performance and without increase of outer module diameter due to geometric limitations of the tunnel.

The requirements are as follows:

- Performance: each inverter 80 kVA peak, 300 A (r.m.s.) peak, torque 350 Nm for the parallel hybrid/ 500 Nm for the electric front axle
- DC link voltage 200 V – 450 V
- Coolant inlet temperature 105 °C (given by the ICE temperature level)
- Modularity (separable housing)

2.2 Integration Concept

The idea is to locate both inverters in between the e-machines without losing the modularity of the parallel and front axle module and requiring only minor geometric modifications. This leads to a circular shaped double inverter (see Figure 3).

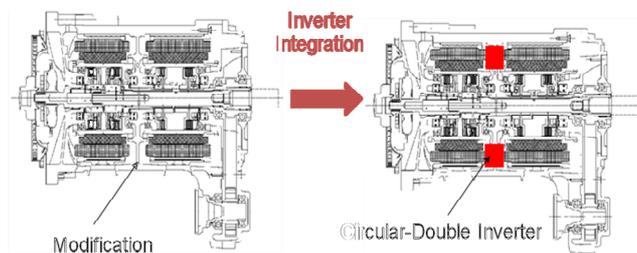


Figure 3: Cross section of the traction module integration concept

A critical issue is the mechanical strength for the hydraulic clutch actuation. To guarantee a precise actuation the radial intermediate fillets between the machines have to withstand high mechanical strength. Finally the axial length of the complete module has to be increased by about 70 mm to get the required inverter volume of about 4.4 litres (see Figure 4). The modifications consider an oil-free ambient for the inverter, and a mechanical, electrical, and thermal coupling to the e-machines. Both resolvers originally located on the left and on the right are packaged at the inner side. The complete inner arrangement is also designed to serve as coupling device to ensure the modularity of the module (separable housing).

2.3 Thermal Simulations

Figure 5 shows the 3D model of the complete traction module and the temperature boundary conditions for the computational fluid dynamics simulation with FLUENT™.

The maximum temperature level of the cooling jacket is 105°C. The fluid circuit is performed as a series connection with the double inverter.

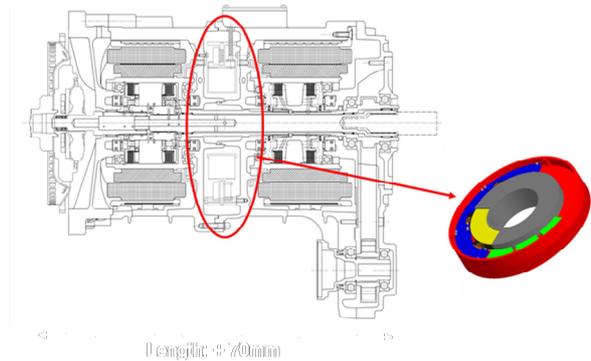


Figure 4: Inverter integration scenario

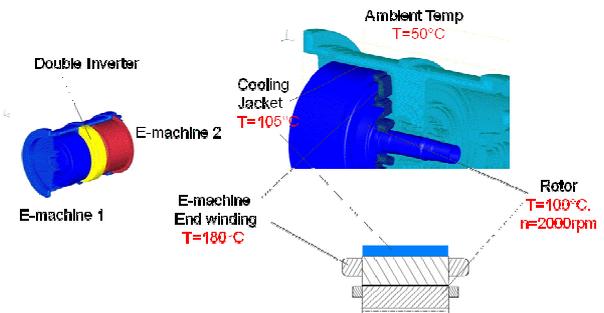


Figure 5: Temperature boundary conditions

Considering the new geometrical situation the simulation points out a maximum temperature of 110 °C at the outer diameter and of 125°C at the inner diameter where the gasket is located (see Figure 6). The radial symmetrical temperature profile determines the thermally coupling of the new double inverter.

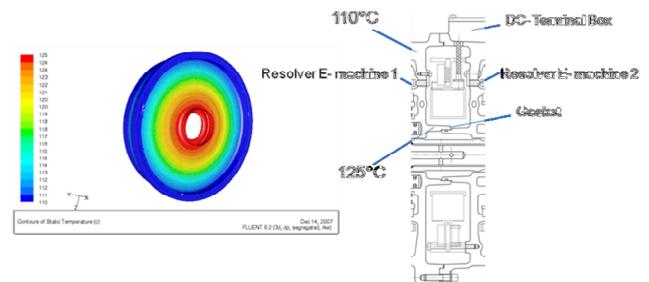


Figure 6: Temperature distribution of modified inner housing

2.4 Inverter

A ring shaped structural element of aluminium forms the inverter housing and the cold plate for the power modules (Figure 7). The coolant is guided within this ring, the water connections are realized without any additional piping. A toroidal or ring shaped polymer film capacitor functions as a central DC link capacitor. Due to costs the preferred capacitor film material is polypropylene. However, this material can only be

operated reliably at temperatures up to 110 °C, respectively up to 120 °C for a limited duration of 1000 hours [6]. A sophisticated thermal management concept applying advanced thermal shielding and cooling techniques is necessary. The same is valid for the current sensors and the control board.

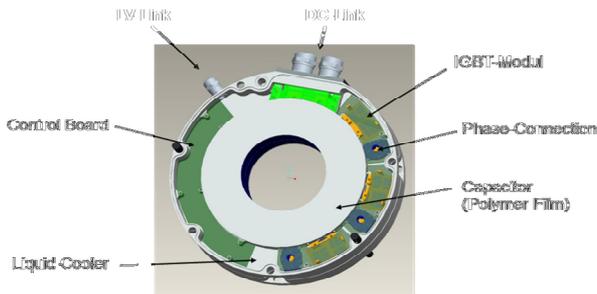


Figure 7: Double inverter layout

Simulations were done by using the software FloTHERM assuming a module stacked as displayed in Figure 8. Four IGBTs and four diodes made of silicon are attached to a DCB substrate by means of soldering.

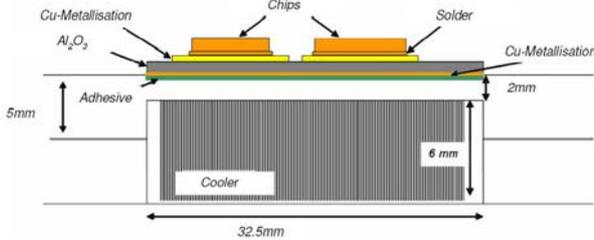


Figure 8: IGBT module

The substrate itself is mounted onto an aluminum cooler using a conductive adhesive. In order to improve the heat dissipation of the cooler, a fin structure, which is passed by a coolant, was worked into the bottom. The number and arrangement of the diamond shaped fins is optimized by simulations to minimize the maximum temperature that chips and solder interconnections would have to endure. However, a maximum pressure loss of the coolant of 30 mbar per power module has not to be exceeded.

Several different patterns and arrangements of fins with a flow rate of 8l/min were tested. First simulations involved designs of densely packed columns of fins, comprising five to six fins each. Maximum temperatures of less than 130°C were reached (Figure 9). However, the pressure drop condition of less than or equal 30 mbar could not be fulfilled.

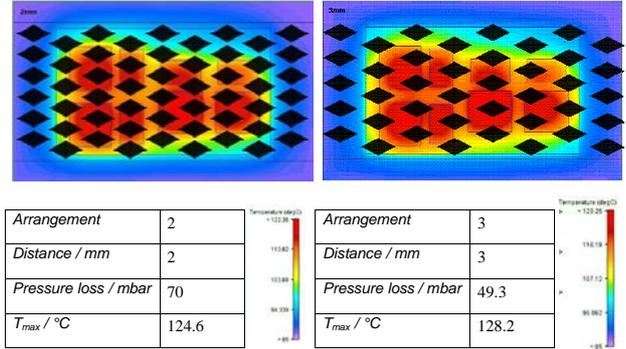


Figure 9: Thermal optimisation investigations

In a next step less densely packed arrangements were examined. A pressure loss of 20 mbar could be achieved for both layouts displayed in Figure 10. The maximum chip temperature was also reduced to about 123°C.

The structure termed “4343434”, due to comprising of seven alternating columns of three and four fins, proved best both in pressure loss (19.4 mbar) and temperature (123.3°C).

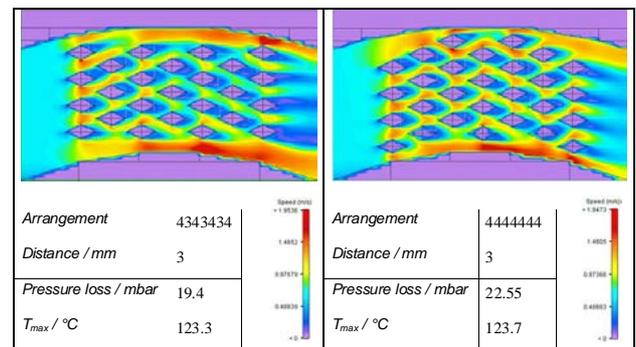


Figure 10: Flow simulations to reduce pressure

2.4 Assembly and internal interfaces

Main challenges beside the thermal issues are the assembly and the internal interfaces. Figure 11 depicts the principle assembly arrangement of the complete drive unit. An adapter plate can be used for axial mechanically coupling the double inverter to the e-machines. This plate can lead the sensor elements, the electric and hydraulic interfaces to the right position and further improve the mechanical stability of these interfaces. The phase terminals can be connected by crimping and additional electrical soldering [7], and via pressure contacts to the inverter. This adapter can also be used as a heat shield and for thermal coupling to the cooling circuit. Preassembled at the e-machine the double inverter can be mounted via screws to the double inverter.

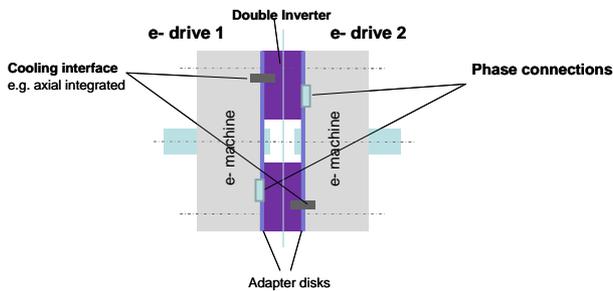


Figure 11: Rough sketch of the double e-drive

3. Application 2: FC Hybrid Powertrain

3.1 Requirements

Beside the separated topology, a smart design for e-drives in FC- and E-vehicles is the joined inverter with own housing on top of the e-machine connected via bus bars. The e-machine is co-axial (Figure 12) or offset mounted to the gearbox (differential and gear sets).

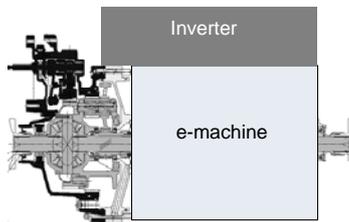


Figure 12: Cross section of a co-axial drive with joined inverter

The geometrical restrictions are not so dramatically in contrast to the hybrid application. The same applies for the thermal situation. Applying an integrated inverter to the “Sprinter” FC transporter of Daimler [8] the requirements are:

- Performance: inverter 130 kVA peak, 435 A (r.m.s.) peak, electric rear axle
- FC-DC link voltage 200 V – 450 V
- Coolant inlet temperature <90°C

3.2 Integration Concept and Inverter

The packaging situation of the rear axle allows an increase of diameter on a partial segment of the stator circumference (see Figure 13). A more compact solution of the concept is to attach the inverter using the cooling jacket of the e-machine.

Figure 14 shows a two-segment radial integration of the inverter using the cooling jacket of the electric machine.

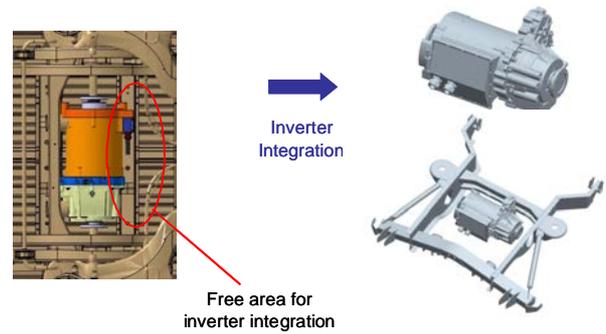


Figure 13: Integration concept

The cooling jacket is modified to get planar areas for the IGBT modules as closely as possible to the coolant. The second segment contains the DC link capacitors. The concept comprises full access to the components. Advantages of the solution are the thermal conditions, because the end windings of the e-machine are shielded by the cooling jacket.

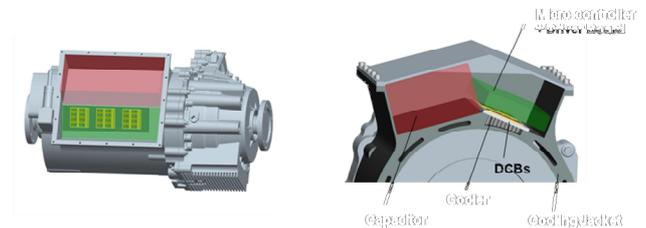


Figure 14: Inverter integration concept - principle arrangement

4. Conclusion

This paper introduces two integration concepts for completely different applications and specifications but with highest package density.

First approach is a *circular shaped double inverter* in between two axial positioned e-machines applied in a multifunctional ICE hybrid powertrain. The concept comprises

- Modularity: both drives are separable
- Assembly: the inverter is preassembled in disc arrangement
- Cooling synergies: the inverter is sharing the cooling with the e-machines with proper hydraulic interfaces
- Electric synergies: combined use of DC Link capacitor, one DC Link terminal
- Highly integrated speed/position sensor

In total a system volume reduction of about 9 litre, and a system weight reduction of 13 kg can be achieved for this application (see Figure 15).

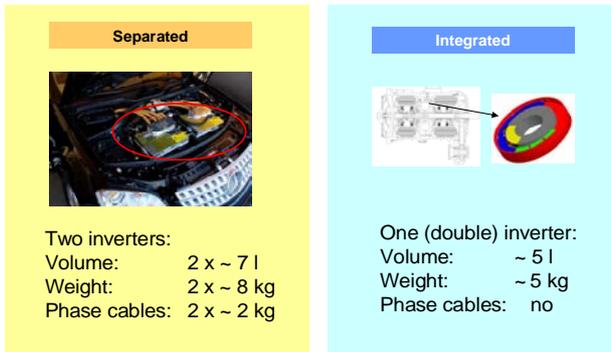


Figure 15: Comparison of separated vs. integrated solution (ICE Hybrid) - estimation

The proposed concept can be applied to all e-machine topologies with two e-machines like e-CVT, electric torque split axles and series hybrid drives. Consequently the double inverter can be prepared applying a single drive by equipping only on inverter side and mechanically sealed with a cover. Further the module can be extended easily with the second drive (e.g. range extender system).

Second approach is an *attached single inverter* for a FC application. The concept comprises

- Flexible packaging to different vehicles: no significant change of e-machine dimensions
- Easier accessibility and serviceability
- Cooling synergies: efficient common liquid cooling of inverter and e-machine
- Electric synergies: one DC link connection
- Application of conventional plane inverter substrates and DC capacitors

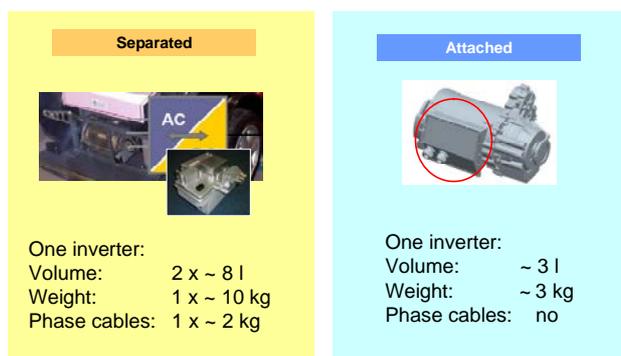


Figure 16: Comparison of separated vs. attached solution (FC Hybrid) - estimation

Radial partial integration at stator periphery allows flexibility to different packaging conditions of the vehicle keeping the motor dimensions. On systems level the volume and weight can be reduced significantly (see Figure 16).

In principle the proposed concept can be applied to all electric-driven axles scaled in required performance.

5. References

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6. Glossary

- ICE Internal Combustion Engine
 FC Fuel Cell
 DC Direct current
 e-CVT electric Continuous Variable Transmission
 DCB Direct Copper Bonding
 IGBT Insulated Gate Bipolar Transistor

7. Acknowledgment

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