Need for Semiconductors in Hybrid Drives Applications

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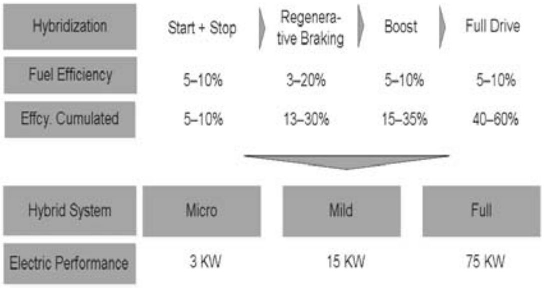
Abstract

Hybrid electrical vehicles (HEV) have the potential to save energy in the automobile. Beside the power semiconductor devices used for the main inverter additional electronic components will be needed in future vehicles. Depending on the power class and required performance of the drive the right semiconductor has to be used. According to the special needs in Hybrid Drives applications future trends like increased junction temperature or new interconnection technologies will be illustrated.

1 Introduction

With upcoming importance of energy saving in future cars as well as CO_2 reduction todays hybrid cars show the potential reaching more efficiency in automotive applications. Today there are existing different concepts of hybridization. Depending on the functionality and power range three systems (μ-Hybrid, Mild-Hybrid, Full-Hybrid) are implemented in available cars. The level of hybridization has direct impact on fuel consumption (fig. 1).



Hybridization	Start + Stop	Regenerative Braking	Boost	Full Drive
Fuel Efficiency	5–10%	3–20%	5–10%	5–10%
Effcy. Cumulated	5–10%	13–30%	15–35%	40–60%

Hybrid System	Micro	Mild	Full
Electric Performance	3 KW	15 KW	75 KW

Fig. 1 Level of hybridization in cars

1.1 Hybrid system architecture

Beside the combustion engine minimum one additional electric motor/generator is integrated in Mild- and Full hybrid cars. Here the electrical motor is driven by battery voltages in the range of approx. 120 V up to 400 V.

For exchanging energy between the 14 V DC power net and the DC high voltage (HV) power net a DC/DC converter is used. Steering the electric motor is realized by using a DC/AC inverter. Optional an additional DC/DC boost converter can be used to increase the battery voltage for higher power ranges.
The hybrid system allows additional auxillary drives realized by additional inverters (DC/AC). New opportunities like ventilating and air conditioning (HVAC), power steering or oil pumps will be possible (fig. 2).
Typically the inverter is realised by six IGBT switches, each with antiparallel diode (fig. 3). The switching frequency of the IGBT's in hybrid drives applications is in the range of 8 -10 kHz. The switches are implemented in power modules well know from industrial and traction applications.

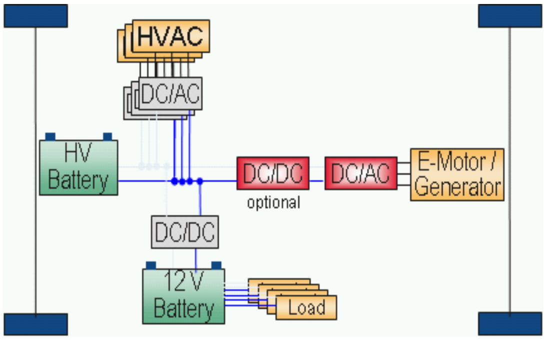


Fig. 2 System architecture of a hybrid vehicle

For DC/DC converters different configurations can be used. H-bridge and half-bridge topologies could be find as well as configurations with active (MOSFET, CoolMOS, IGBT) and passive components (diodes). The optional booster mostly is realised as a half-bridge with two switches (for e.g. 600 V IGBT / diode or 600 V CoolMOS).

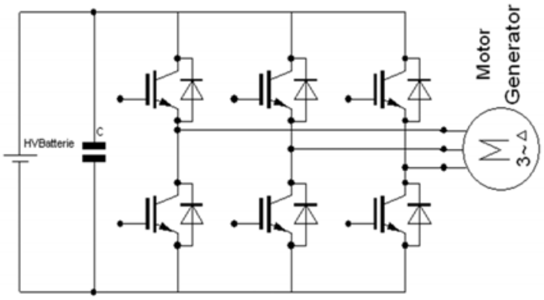


Fig. 3 Inverter configuration (DC/AC) with six IGBT/diode switches

An optimized DC/DC behavior with low voltage ripple can be reached by increasing the switching frequency up to 100 kHz. Therefore low power DC/DC converter topologies are realized by MOSFET devices.

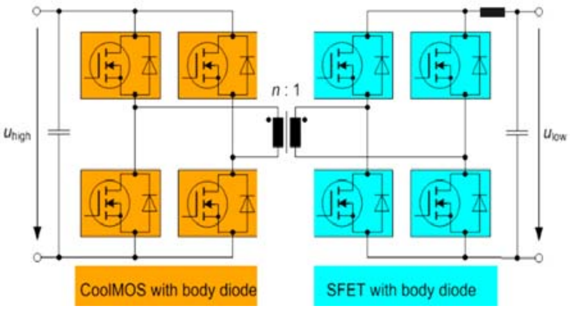


Fig. 4 DC/DC configuration (dual active bridge)

The switching losses of MOSFET's are much lower compared to IGBT's in this operation mode.

For example the DC/DC converter (between 14 V and HV power net) can be realized with two H-bridges (dual active bridge). The low voltage side is realized by e.g. 40 V MOSFET's and the HV-side is realized by e.g. 600 V CoolMOS devices (fig. 4).

1.2 Requirements for HEV power electronics

Besides cost and performance, quality is a major topic for HEV power electronics. Although expected quality level and lifetime are same for all components, the environmental stress that determines the requirements for each component might be very different. As with most automotive components the requirements for power semiconductors vary between different mounting places and cooling conditions (Fig. 5).

In terms of thermal resistance liquid cooled systems show significantly better behaviour than air cooled systems. Due to the low losses mild hybrid systems can still be cooled with forced air cooling. Full hybrid systems need liquid cooling to dissipate the power.

	Trunk mounted with forced air cooling	Engine compartment with seperate liquid cooling	Engine mounted with engine coolant	Transmission mounted with transmission coolant
Ambient temp.	-40 - 85°C	-40 - 105°C	-40 - 105°C	-40 - 140°C
Coolant temp.	-40 - 65°C	-40 - 85°C	-40 - 125°C	-40 - 150°C
Thermal cycles	Medium	High	High	Very high
Power cycles	Medium	High	High	High
Vibration	5g	10g	10g	20g
Shock	50g	100g	100g	400g

Fig. 5 Requirements for different mounting and cooling conditions of power electronics

2 Power elctronics for HEV applications

2.1 Power semiconductors

To improve the efficiency of a hybrid drive it is important to reduce the losses in the power semiconductor. MOSFET and IGBT are the predominant power semiconductors in HEV applications. Due to the uni-polar characteristic the switching losses of a MOSFET are significantly lower than those of an IGBT. As a result applications with high switching frequency (>100 kHz) are the domain of MOSFETs while applications with low switching frequencies (<10 kHz) are typically dominated by IGBTs. The unipolar characteristic also leads to a resistive transfer characteristic. In contrast the transfer characteristic of the IGBT shows a threshold voltage of about 0,8 V due to the pn junction at the back side of the IGBT. Only above this voltage a resistive characteristic can be observed (fig. 6).

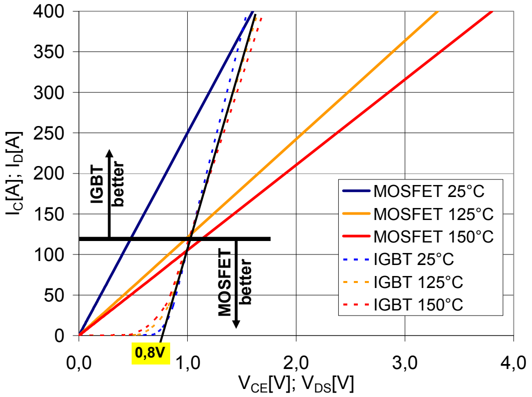
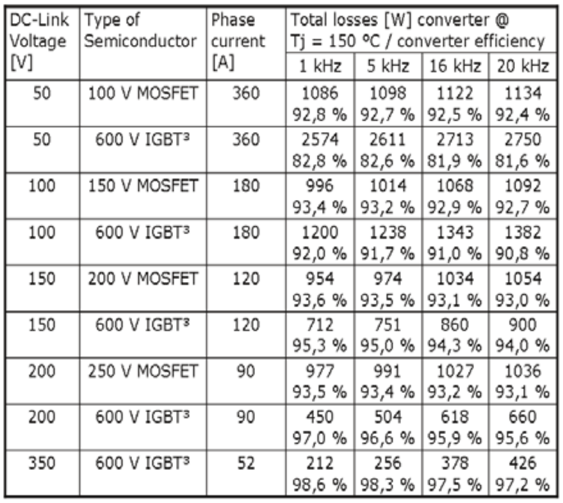


Fig. 6 Conduction losses of same area 600 V IGBT/Diode and 250 V Trench MOSFET

While the resistive part scales with the blocking voltage the threshold is independent from it. Therefore IGBTs are less suitable for low voltage applications then MOSFET. To compare the two technologies the losses in a converter which is equipped with the same silicon area can be used as a figure of merit. Figure 7 shows the results of a simulation for a 15 kW converter equipped with a silicon area of 420 mm² for different system voltages and switching frequencies.



DC-Link Voltage [V]	Type of Semiconductor	Phase current [A]	Total losses [W] converter @ Tj = 150 °C / converter efficiency			
			1 kHz	5 kHz	16 kHz	20 kHz
50	100 V MOSFET	360	1086 92,8 %	1098 92,7 %	1122 92,5 %	1134 92,4 %
50	600 V IGBT³	360	2574 82,8 %	2611 82,6 %	2713 81,9 %	2750 81,6 %
100	150 V MOSFET	180	996 93,4 %	1014 93,2 %	1068 92,9 %	1092 92,7 %
100	600 V IGBT³	180	1200 92,0 %	1238 91,7 %	1343 91,0 %	1382 90,8 %
150	200 V MOSFET	120	954 93,6 %	974 93,5 %	1034 93,1 %	1054 93,0 %
150	600 V IGBT³	120	712 95,3 %	751 95,0 %	860 94,3 %	900 94,0 %
200	250 V MOSFET	90	977 93,5 %	991 93,4 %	1027 93,2 %	1036 93,1 %
200	600 V IGBT³	90	450 97,0 %	504 96,6 %	618 95,9 %	660 95,6 %
350	600 V IGBT³	52	212 98,6 %	256 98,3 %	378 97,5 %	426 97,2 %

Fig. 7 Losses in a 15 kW converter

2.2 Interconnection technologies

Today power semiconductor modules usually contain several IGBTs and diodes, which are soldered onto a metallised ceramic substrate. To connect the top side of the chips wire bonding is state of the art. Multiple substrates are connected to a baseplate by use of soft-solder joints (fig. 8).

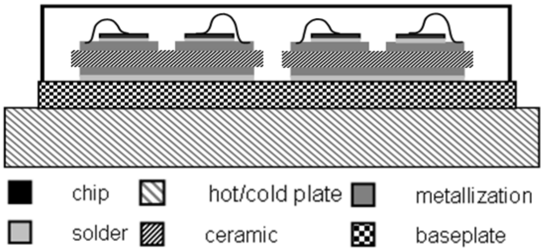


Fig. 8 Schematic overview (cross-section) of a module mounted onto a hot/cold plate

Changing the maximum allowable junction temperature of the power semiconductor will directly change the thermal stress on the interconnection of the chip surface. A typical wear out effect at the chip surface is the wire bond lift off.

For the introduction of a maximum junction temperature of 175 °C the wire bonding process has already been improved from standard wire bonding to the IFX new generation wire bonding (fig. 9). For future designs results of the low temperature joining process are promising. As can be seen in figure 9 the tests were still ongoing after 70000 cycles with a temperature swing of 130 °C.

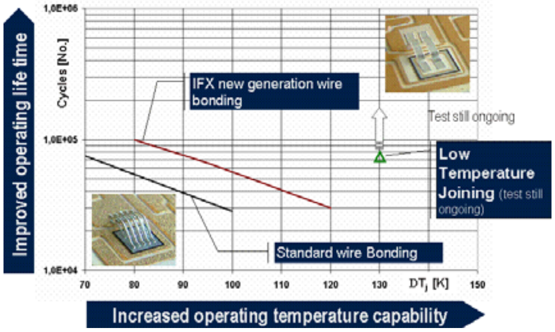


Fig. 9 Improvement of power cycling as a result of new interconnection technologies

Over the lifetime of DCB modules the layers are prone to recurring mechanical stress, due to the ongoing thermal cycles. Caused by the current flow in the semiconductor and the resulting heat up, the materials used such as copper, ceramics, silicon and aluminium expand with their different coefficients of expansion.

This may lead to premature solder fatigue between the DCB substrate and the baseplate. The result is delamination of the solder layer and the increase of the thermal resistance caused by this. Finally, the component fails due to overheating.

An important qualification test for semiconductor modules is the so called thermal shock test (TST). Power semiconductors for hybrid drives bear requirements of up to 1000 cycles of thermal shock. This requirement can not possibly be achieved with a standard DCB module construction.

One solution is the use of a so called “improved” Al_2O_3 - DCB in conjunction with a copper baseplate. This combination of materials is mainly suitable for mild hybrid systems and some full hybrid systems. Figure 10 shows clearly that an “improved” DCB contributes to a much advanced thermal cycling capability.

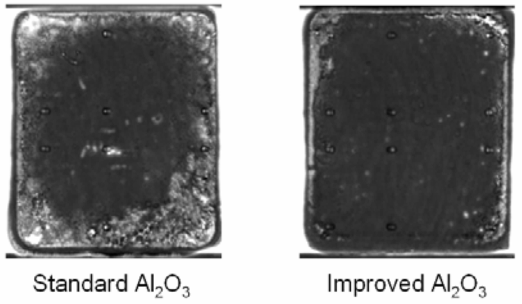


Fig. 10 Ultrasonic scan of solder delamination after TST for Al_2O_3 - DCB on copper baseplate

When designing the power semiconductor module particular consideration needs to be given to the load profile during the lifetime of the hybrid vehicle. Once the required profiles are available detailed in passive temperature fluctuations and current profiles, a suitable combination of materials substrate (DCB) / baseplate can be determined.