Effects of a SiC TMOSFET tractions inverters on the electric vehicle drivetrain.

Alexander Nisch, Christian Klöffer, Jörg Weigold, Wolfgang Wondrak, Daimler AG, Research and Development, Hanns-Klemm Straße 45, 71034 Böblingen, Germany, alexander.nisch@daimler.com

Christian Schweikert, Laurent Beaurenaut, Infineon AG, Research and Development, Am Campion 1-12, 85579 Neubiberg, Christian.schweikert2@infineon.com

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Abstract

Due to the constantly increasing demand for the electrical range and to the restricted installation space, the request to the energy efficiency of a traction inverter will increase. Silicon carbide MOSFETs are considered as the most promising semiconductor devices for future traction inverter applications. In this paper we discuss the potential and challenges of a three-phase voltage-source-inverter based on trench SiC MOSFETs (SiC TMOSFET) under automotive constraints, considering the complete drivetrain.

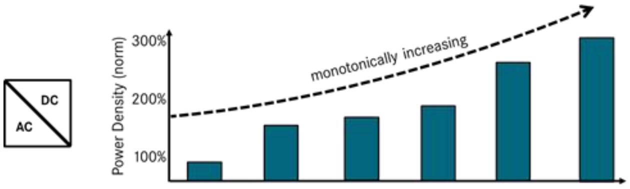
To achieve the optimum efficiency the switching behaviors of different gate controls are investigated. Based on the results, a significant efficiency improvement for an electric vehicle application is possible, this could be confirmed by measurements.

1. Introduction

The rising range requirements and the finite installation space in electric driven vehicles result in higher efficiency requirements on the drivetrain. One option is to improve the efficiency of the traction inverter by SiC TMOSFET. The majority of electric drivetrain applications in the automotive industry operates in the range up to 450V dc-link voltage. For this voltage range a sufficient number of 750V technology based Si-IGBT semiconductors and modules are available on the market. In case of SiC TMOSFET semiconductors it looks quite different. The availability of 750V rated SiC TMOSFETs and modules is small. The purpose of this work is to evaluate the potential of 1200V SiC TMOSFETs in conjunction with an automotive qualified module, which is conform to both voltage requirements up to 450V and 800V. The special challenge was to design the DCB-layout in the existing module to meet the requirements in Tab.1 with 1200V SiC TMOSFETs. Based on this design, the efficiency and its impact on system costs have been assessed.

Mech. Traction Power	DC-Link Voltage	Fundamental Frequency	Switching Frequency
240 kW	250 – 470 V 550 – 850 V	1200 Hz	10 kHz
Peak Phase AC Current [30sec]	Continue Phase AC Current	Max. Current [1ms]	Max. DC Current continue
$550A_{rms}$	$300A_{rms}$	1600A	450A
Max. pressure drop @10l, 65°C	Min. rate of flow @65°C	Max. Temp. Cooling	Min Temp. Cooling.
<220 mbar	10 l	75°C	-40°C

Table 1: Drivetrain Requirements



Year of SoP	2009	2012	2014	2016	2020	> 2025
Power Density	100 %	160 %	175%	185%	more	even more
Volume	4.1 l	3 l	3.8 l	3.3 l	less	even less
$U_{DC,max}$	390 V	405 V	410 V	410 V	more	even more
$I_{Ph,10s,max}$	215 A	240 A	325 A	300 A	more	even more

Fig. 1. Continuous increase of automotive traction requirements

2. Procedure

2.1. Module Design

The power module as a part of the traction inverter contributes significantly to the efficiency and functionality of the system. For enabling easy design in a well-established form factor, scalability, a lifetime as given today by IGBT modules, robust functionality, reliable switching behavior, and an adequate thermal setup are important. With the example of Infineon's Hybridpack Drive™ power module family a power capability of 220% is enabled by the upcoming automotive silicon carbide version (CoolSiC™) see fig. 2. The CoolSiC™ module is the basis for the investigations reflected in this paper. Beside the general design considerations for a power module, this chapter will focus on module-related targets arising from applying the Automotive CoolSiC™. In complex systems such as the electrical drive train, commercial targets can not only be fulfilled on component level. Instead the whole system cost shall be considered. The power module as a part of the traction inverter contributes significantly the efficiency of the system. Efficiency increase leads directly to lower cooling cost, lower battery cost and indirectly to the cost for the design space and the cost weight which is directly linked to the required battery capacity in case of an Electric Vehicle [EV] or the CO_2 budget of a Plug-in Hybrid Vehicle [PHEV]. Another contributor the commercial aspect is scalability. New form factors for different power- and voltage classes are leading to a significant R&D effort. With the example of Infineon's Hybridpack Drive™ power module family a wide range of scalability is given. The IGBT based versions are offering a power scaling range of 120% within the 750V class.

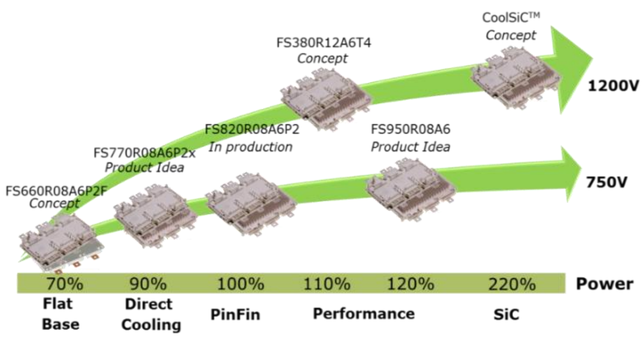


Fig. 2. Power scalability with CoolSiC™ Technology related with progressive power module design.

The upcoming Automotive Silicon Carbide version (CoolSiC™) enlarged the scaling range by a further factor 2 up to 220% within the 1200V class. The SiC module is the basis for the investigations reflected in this paper. Despite today's higher cost for SiC based power modules, system cost reduction can be achieved utilizing above mentioned benefits. Commercial aspects are enabled by reaching the design targets on various level. Vehicle and system related items will be considered in the following chapters. Beside the general design considerations for a power module [1], this chapter will focus on module related targets related to the challenges arose by applying the Automotive CoolSiC™ technology. In case such a revolutionary development step is made, the degree of freedom for potential development risks shall be maintained low. For that reason, Infineon has decided to apply

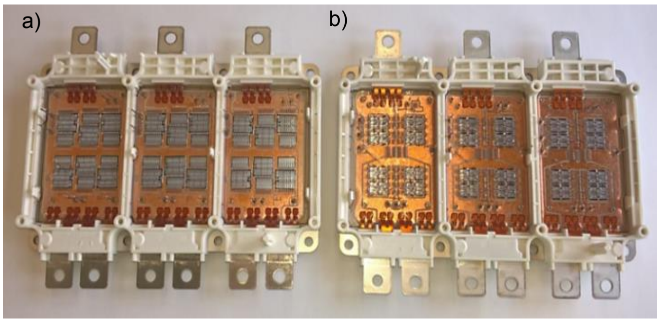


Figure 2: Hybridpack DriveTM a) based 750V IGBT/Diode b) based 1200V CoolSiC™.

SiC on a known package platform with acceptable parasitic behavior – the Hybridpack Drive™. Starting on this basis, the main design targets are: Enabling system efficiency increase by 3 to 5%, sufficient live time as given today by IGBT modules, robust functionality, reliable switching behavior and an adequate thermal performance. The module under assessment is the 1200V prototype of the Automotive Silicon Carbide (CoolSiC™) Hybridpack Drive™ version with 3 phases, each switch consisting of 8 SiC TMOSFET in parallel.

2.3 Life time

Reaching the expected lifetime of 15 years over all mission profiles, the design of module and chip is a trade-off between the performance and the robustness of the SiC MOSFET. In case of the chip design, the mayor performance criterion is the R_{DSON}*A which is a trade-off with the threshold voltage, the gate oxide (GOX) thickness, the cosmic ray robustness and the short circuit capability. Due

to today's intrinsic defect density of the SiC base material also a good tradeoff for the die size must be found. The first generation of Infineon's Automotive CoolSiC™ chips, it was decided to design a mid-size chip. This leads to a parallel connection of chips in the power module design. The impact on the functionality of this design strategy is discussed in the following chapter.

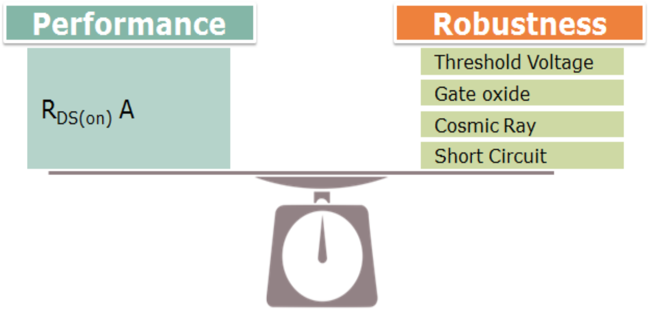


Figure 3: Balance between performance and robustness.

But first, let's have a short look to the GOX. One measure to improve the lifetime is the increased thickness of the gate oxide. This reduces the gate stress of the GOX and improves the cosmic radiation robustness. A thick GOX increases the physical break down voltage [Vbr] significantly above the rated voltage of the module – in this case 1200V. This fact differentiates the SiC module design from the IGBT design where the voltage rating of the module is equal to the physical breakdown voltage. The headroom of some hundred volts in SiC ensures the robustness over lifetime on one hand – on the other hand, the headroom offers some degree of freedom designing the system for fast switching by allowing a slightly higher VDS-max. peak for a limited amount of time.

2.4 Functionality

By applying several chips in parallel the power targets given by the application are reached. The fast switching is enabled by the low chip capacitances of the Silicon Carbide TMOSFET. In context with package related parasitic inductance and capacitance, special care needs to be taken designing the chip, module and system. An inappropriate module design can lead to destructive chip-to-chip oscillations see fig. 4.

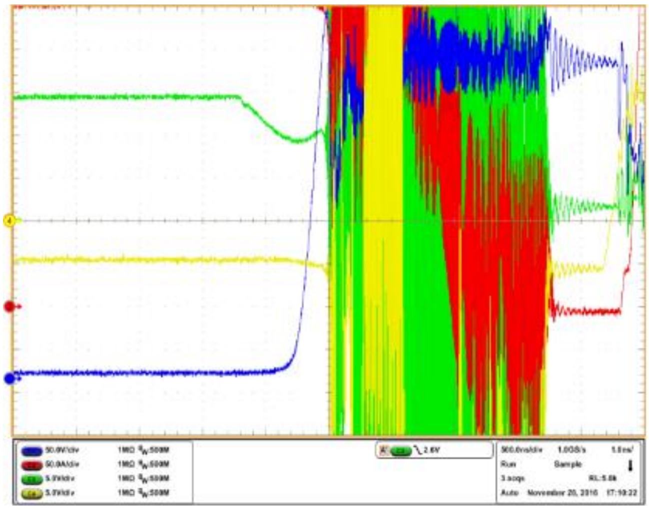


Fig.:4: Example of a turn-off measurement with non-optimized design, parasitic capacitive coupling into the gate leads to oscillations

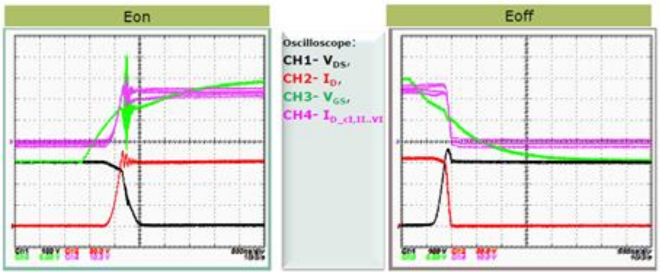


Figure 5: Imbalance of current distribution

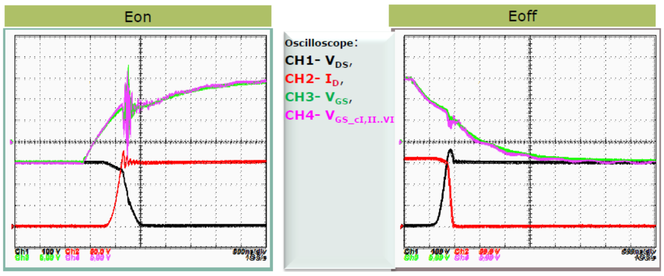


Figure 6: Oscillation due reduced capacity

Non-symmetrical design can cause imbalanced current distribution and thus to unwanted ringing and balancing currents, as illustrated in figure 5. Also, timely equals switching of all chips within one switch system can lead to oscillation see fig. 6. A ceramic substrate [DCB] layout with symmetrical current and parasitic inductor distribution (L1.x…L4.x, fig. 7) avoids current feedback and imbalanced current between the switch-systems (groups of paralleled chips forming one switch). Low stray-inductance in general reduces the voltage overshoot caused by fast switching. A sufficiently low parasitic drain-source capacitance reduces the risk of forming "tank capacitors" feeding

unwanted charge into the gate during the switching events. Short, symmetrical and low inductive gate connections are avoiding current imbalance between the chips within one switch-system and chip-to-chip oscillations. Considering those basic rules, very fast switching across the desired operating range with low losses is possible with SiC TMOSFETs.

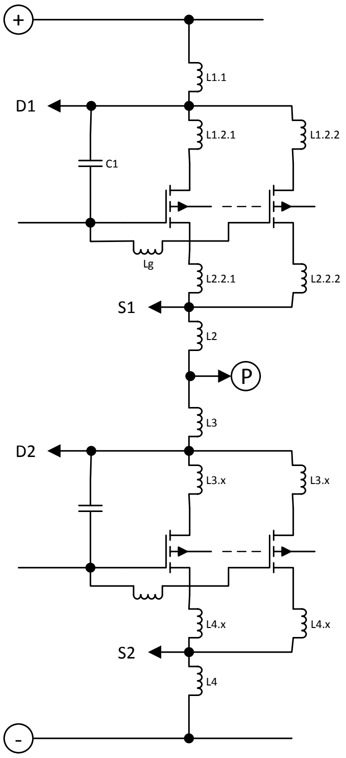


Figure 7: Parasitic inductor distribution

2.3 Thermal performance

Although silicon carbide offers the possibility to operate at very high junction temperatures, the package technology must be adapted to the related high power density. The small local heat source must be able to dissipate the thermal energy to the environment. This is enabled by replacing standard DCB ceramics, typically Al_2O_3 with λ(25°C) ~24W/mK to Si_3N_4 with λ(25°C) ~ 80W/mK. In combination with the pin-fin base plate of the HybridPack™ Drive module (copper material with nickel plating) an adequate thermal performance can be reached.

2.4 Switching behavior

Optimization for fast switching is a challenging task. There are various major contributors to the switching behavior: The gate driver, the gate resistor, the handling of voltage overshoots caused by inductive parasitic and external measures, such as the characteristics of the busbar, the DC-link capacitor and, if applied, a snubber circuit. Optimization concerning the over-voltage peak is required to enable fast switching. The application of a snubber circuit is one possibility, it can be integrated in three ways: First, the snubber circuit is connected to the plus and minus terminals of the module; second, it is assembled on the gate driver board and last, it is integrated into the power module. The first option is the most popular one but at the same time the least effective one. The reason for the low efficiency is the parasitic inductance between the connection point of the snubber and the SiC TMOSFETs. The integration into the module is from today's perspective the most efficient one in terms of handling the overshoot, but not applicable due to cost, space, feasibility and design risks. The best trade-off between snubber efficiency and applicability is integration into the gate driver board. To enable this design various pre-conditions shall be fulfilled. The pinout of the power module must enable direct access to the SiC TMOSFETs and their position shall not disturb the low voltage design on the PCB. At the same time the pinout shall not harm the functionality as described above.

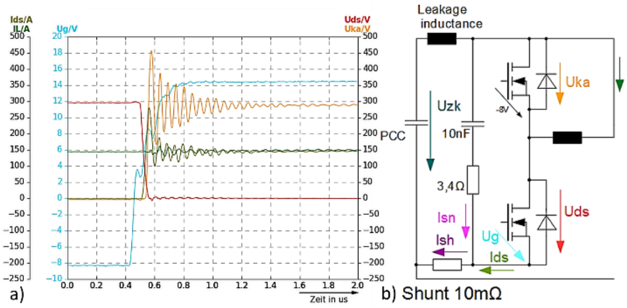


Figure 8: a) Measurement without snubber circuit, b) Snubber circuit and measurements setup; V_{ds}, red; V_{ka}, orange; I_{ds}, green; V_g, cyan

The first measurements without a snubber show that the diode voltage oscillates at turn-on (fig. 8). Based on the measurement the parasitic inductance of the snubber circuit based on capacitor and resistor is calculated C_s=10nF and R_s=3.4Ω, the snubber circuit is implemented after option one. The improved switching can been seen in fig. 9.

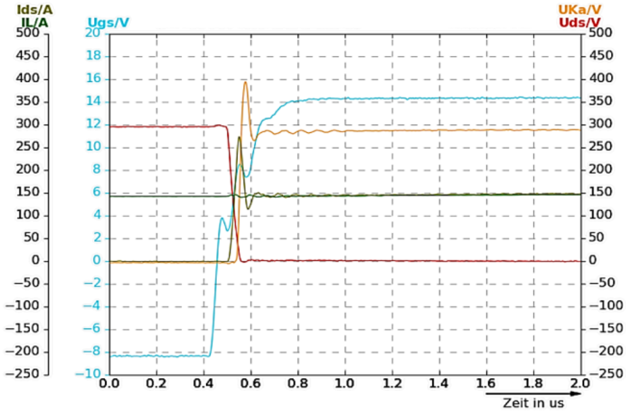


Figure 9: Switch on with snubber

The characterization process of a power module consists of several steps with various measurement and optimization steps: First, the Lab characterization on a standardized measurement setup to judge the functionality and robustness as previously mentioned. Further, the characterization with the application specific setup, such as gate driver and DC-link capacitor is executed. Within there, the first optimization of the switching behavior is performed. Finally, the deployment in the target inverter and operation on the test bench with the target motor and later on in the vehicle are evaluated. In the following, some aspects concerning the optimization towards fast switching are discussed. There are various major contributors to the switching behavior: The gate driver, the gate resistor, the handling of the voltage overshoots caused by inductive parasitic and external measures, such as the characteristics of the bus bar, the DC-link capacitor and, if applied, a snubber circuit In the following figure 10, the influence of the gate driver on the example of an over-current switch-off event at V_{DC}=850V, I_d=1200A, and R_{gOFF} = 5Ohm is shown for the standard lab evaluation equipment versus a gate driver used for industrialization. In case of custom driver IC, the switching energy amounts to E_{OFF}=168mJ at di/dt=8kA/µs and dv/dt=6.5kV\µs. In comparison to that, the Infineon standard setup comes to E_{OFF}=140mJ at di/dt=11kA/µs and dv/dt=7.8kV\µs. Beside the gate driver, the influence of the gate resistor must be known. The SiC TMOSFET is well controllable with the gate resistor. The switching characteristic during ON and OFF switching can be controlled well separately. In order to identify the possible potential of SiC, the gate resistor is reduced until reaching the maximum gate drive performance. The reverse voltage was not exceeded, as the selected DC-link voltage was non-critical shows in figure 11.

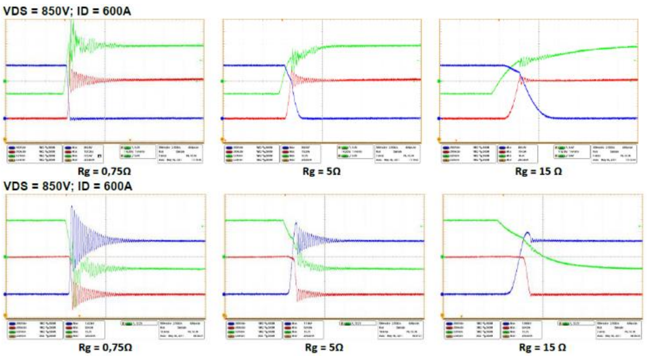


Figure: 10: switching behavior can be controlled well over a wide operating range. Top: OFF; Bottom: ON; blue: VDS, green: VGS, red: ID.

The potential of reduction of switching losses with higher voltage gradients is depicted in figure 12. Compared with a standard design of 5kV/µs the switching losses could be reduced by over 70% in the inverter with lower gate resistor.

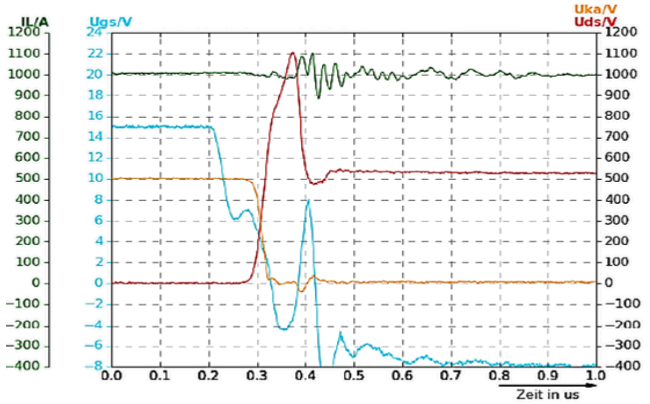


Figure 11: Switch off U_{DS}, 510V DC-link voltage and I_{DS}=1000A, T_j=25°C

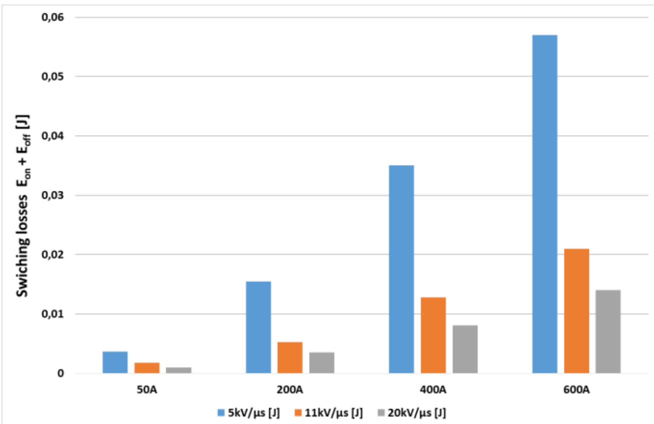


Figure 12: Reduction of switching losses for different voltage gradients at DC-link voltage 450V, T_j=110°C

The current design of the dielectric strength of automotive electrical machines is based on voltage gradients up to 5kV / µs. Due the trend to integration of inverter and electrical machine and resulting reduced inductance in the ac wiring this shall be investigated further.

2.5 Simulation

Based on the driver configuration for safe shutdown at V_{DC}=850V, I_D=1200A and V_{DC}=510V, I_D=1200A, the resulting temperature-dependent switching and conduction losses have been used for further system level simulation. To calculate the semiconductor losses for each working point (in torque and speed) in order to enable drive cycle calculations, the specific electrical values of the electrical machine I_d, I_q, U_d and U_q have to be identified. Between the start and target angle position of the rotor linear interpolation is carried out with the PWM frequency resulting in a reference period. Taking a modulated star point voltage into account, the current and voltage of the reference periods can be determined via the dq transformation dependent on the angular position. The relative duty cycle for a half bridge is calculated based on the voltage, from which it is possible to calculate the currents and losses in each device. In figure 13 is plotted the difference from a Si Inverter and SiC based inverter at 325V DC-link voltage for the same electric machine.

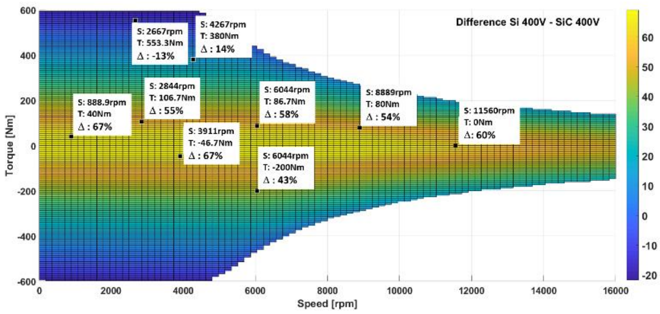


Figure 13: Difference power losses Si 400V and SiC 400V Inverter.

The design of the SiC TMOSFET inverter in this consideration leads to higher losses at the speed-torque operation limits compared with an IGBT based inverter (negative loss reduction potential), whereby a 1200V SiC MOSFET is compared with a 750V IGBT. In contrast, in the case of 1200V SiC TMOSFET operated at 800V DC-link, an advantage is given in this configuration for the SiC inverter over the complete speed-torque map (figure 14). With the power loss results for the inverter it was possible to calculate the energy consumption over the worldwide harmonized light vehicle drive cycle [WLTP class 3] for a heavy sports utility vehicle [SUV].

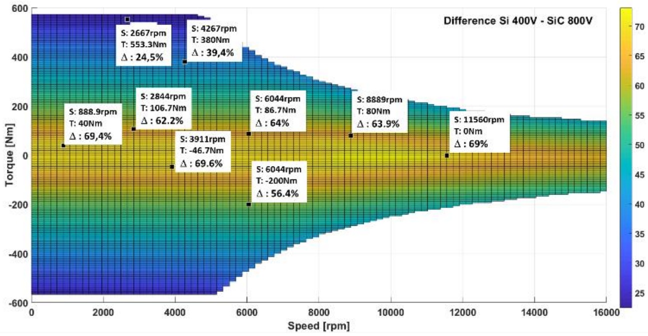


Figure 14: Difference of power losses between Si 400V and SiC 800V Inverter.

In figure 15 the frequency of working points within the characteristic speed-torque map of the electrical machine is shown (diameter of the red points is the frequency of working point). The pie charts show the loss distribution (switching, conduction losses semiconductor, conduction losses bus-bar, losses in the DC-link capacitor...) for each working point.

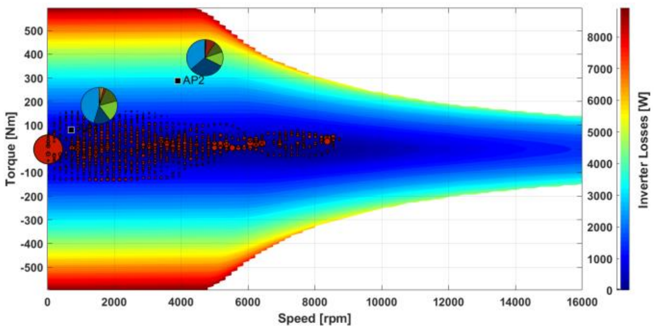


Figure 15: Working points WLTP for an electrified heavy sports utility vehicle.

Comparing the energy consumption for an electrified a heavy sports utility vehicle over a WLTP cycle for 400V and 800V DC-link voltage with different semiconductor technologies the potential of energy consumption could be identify the results are shown in figure 16. An energy consumption reduction in the inverter by 63% in a 400V DC-link system with 1200V SiC TMOSFET leads to savings of 6,3% in the drive cycle, an 800V system with 1200V SiC TMOSFETs leads to a reduction of energy consumption by 69% in the inverter and in

the vehicle to a reduction of energy of 7,6%. The effect of reduction of energy consumption on vehicle side is somewhat underestimated for SiC, because the effect of weight reduction of the battery system was not taken in account in the drive cycle simulations. It must be taken in account, that in case of 400V with 1200V SiC, the SiC area is double and the theoretical inverter power is double.

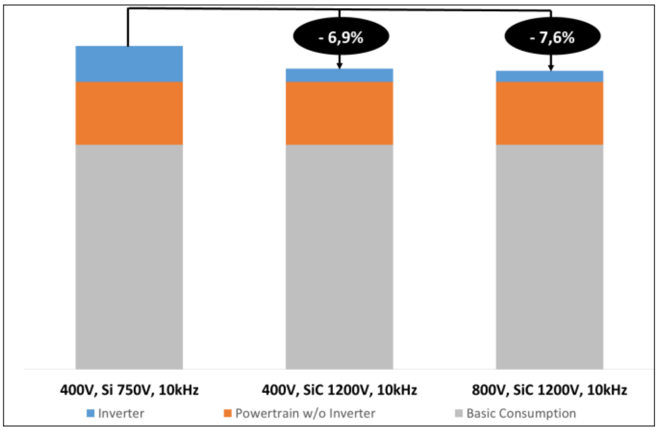


Figure 16: Reduction of energy consumption on vehicle side with SiC TMOSFET technology

2.6 Measurement

To verify the simulation, measurements with an existing electrical machine have been performed. The measurement of power losses of the inverter are done on an electrical machine emulator using the parameters of a well-known. The simulation model and the emulator model are usually based on the assumption of a fundamental wave model, non-linear effects caused by saturation of the magnetic circuits in the motor resulting from magnetic fields are ignored. The difference between simulation and measurements results up to 1500rpm is shown figure 17. The difference in this range are of the order of the measurement tolerance.

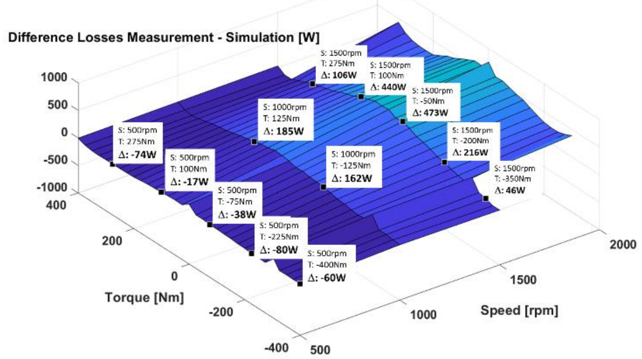


Figure 17: Comparison of measurement and simulation results

2.7 Cost considerations

Wide band gap semiconductors such as SiC diodes or MOSFETs are used in renewable energy generation. By this a more efficient supply of energy, is already also commercially available. In the automotive industry the demand for efficient components is also increasing due to new requirements from certification standards. In the past, the costs and availability of SiC components for the automotive industry were not attractive. Due to increasing production numbers and the increasing requirements for efficiency, SiC is reported to be attractive for future projects [3]. Another factor is the discussion of the introduction of an 800V intermediate circuit voltage, which is due to the significantly better efficiency compared to 800V Si, as well as the significant advantage of the current carrying capacity of SiC MOSFET. In this work, SiC was compared to a 400V Si IGBT inverter and for an 800V system. It was considered for an introduction scenario in 2023. As shown in figure 18 a SiC traction inverter based on an example of a 240kW electric machine, both in a 400V and an 800V system, is more expensive.

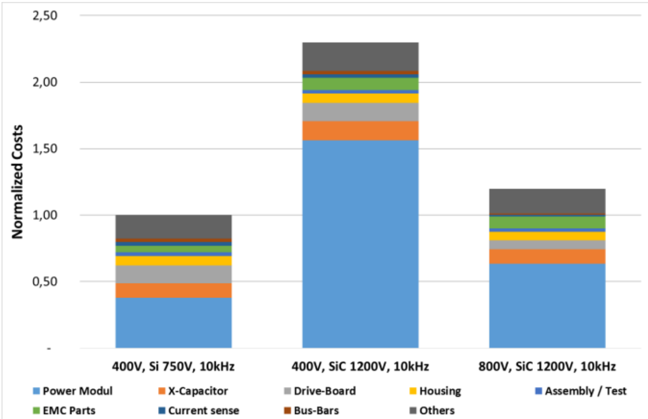


Figure 18: Cost of inverter for 400V and 800V DC-link voltage system with SiC compared to a 400V IGBT Inverter

The additional costs in an 800V system related to the efficiency increase looks attractive. Under the assumption of identical driving range a system cost analysis leads to cost reduction potential. The system cost development as given in figure 19.

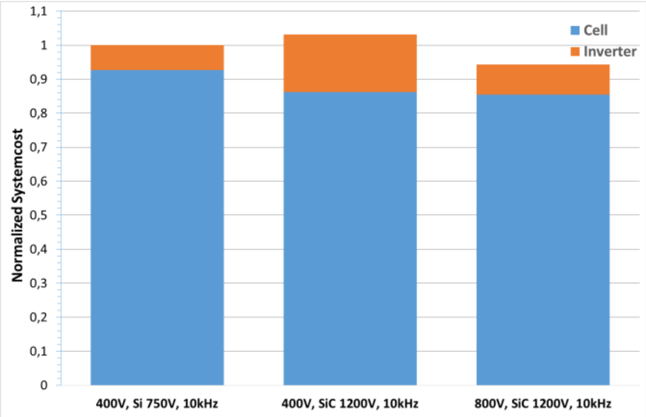


Figure 19: System costs for different voltage and Si and SiC based Inverter taking into account the cost of energy in the battery.

3. Conclusion

SiC semiconductors and especially SiC TMOSFETs (used in this investigation) reduce the losses in a traction inverter. The cause for this improvement is the significant reduction of switching losses. The reduction of conduction losses in a wide range of current could be achieved, this reduction is dependent on the intersection point of the conduction characteristics. As a result, the increase in efficiency is dependent of the mission profile, the degree of load dependent on vehicle parameters and drive cycle. With higher load in the driving cycle, the benefit of efficiency improvement from SiC compared to an IGBT is lower. This interrelation can be optimized either by a further reduction of the R_{DSON} or by paralleling additionally MOSFETs, which leads to significant additional costs. The design of paralleling SiC TMOSFET is very well controllable. The potential of efficiency improvement by reducing switching losses has not been fully reached, due to the limitation by the used gate driver. In case of a DC-link voltage of 800V, an inverter based on SiC MOSFETs is attractive from the point of view of efficiency and costs. An application with a DC-link voltage of 400V is stronger dependent on the cost development of the battery cells and the cost development of SiC, as well as the availability of optimized SiC MOSFET with adapted R_{DSON} in the 450V DC-link voltage class. The impacts of high switching gradients dv/dt on EMC, insulation materials and the winding and ball bearing construction has to be examine. The investigations show that by increasing the switching gradient, the parasitic inductance between the X-capacitor and the semiconductor should be further improved. The performance increase provided by SiC at inverter level may become a major lever for the broad scale adoption of this technology. Still, it should be developed further to meet the stringent constraints required by the automotive industry in terms of lifetime. Robustness to cosmic radiations is a particularly representative example of the performance / robustness trade-off. High-voltage power devices are susceptible to single-event burnout (SEB) due to high-energy particles coming from the space. Robustness against cosmic radiations is therefore a key parameter when dimensioning a power switch. The cosmic ray robustness of a power switch can be improved by increasing the breakdown voltage of the transistor (at constant system use). Physically, this can be realized on a SiC MOSFET by increasing the thickness of the epitaxial layer. This on the other hand has a negative effect on the on- resistance and eventually on the performance of the switch. Compared to a typical IGBT technology however, the performance impact is proportionally less important, leading to a more favorable performance / reliability trade off curve, especially in the 1200V voltage class (or higher).

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