INCREASED SYSTEM EFFICIENCY BY AN 800 VOLT AXLE DRIVE CONCEPT

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ABSTRACT

The worldwide electrification of the transport sector requires the development of highly efficient and cost-effective electrified powertrain solutions. A voltage level of 800 V in the traction system enables the advantages of fast charging and makes it possible to reduce the cross sections of the conductors. Since the battery still causes most of the costs of an electric drive, it is important for range considerations to use the energy supplied by the battery in the most efficient way for powering the drivetrain. The efficiency of the transformation from electrical to mechanical energy is therefore relevant for the development. To increase the efficiency the power losses must be reduced. The power losses of the inverter have to be kept on a low level, while the harmonic losses of the electric motor have to be reduced. The 800 V system voltage level offers the possibility to achieve both goals, if the silicon carbide (SiC) technology is used in the inverter. Due to better electrical properties of the semiconductor material, a SiC inverter is basically more effective than a silicon (Si) inverter due to lower conduction losses. The SiC technology enables furthermore higher switching frequencies which increase the efficiency of the electric motor by reducing the harmonic losses. The combination of the silicon carbide semiconductor material properties, a module design which is optimized on efficiency and the improved operation point control with additional free parameters leads to a highly efficient traction system consisting of inverter and electric motor. For an optimized design the system efficiency of the drivetrain can be increased up to 4 – 8 % in the WLTP cycle. In order to optimize and predict the lifetime of the drivetrain accurately, the increasing electrical loads of the motor must be analyzed. Vitesco Technologies will contribute to the efficiency increase of electrical powertrains by developing an extended modular concept for an 800 V axle drive.

1 EFFICIENCY OF THE ELECTRICAL DRIVE AS A DRIVER OF INNOVATION

The success of battery electric vehicles (BEV) depends on two main aspects. The acquisition costs and the customer usability of the cars. The battery range of BEVs remains one of the most important features for the customer usability.

The battery range defines the maximum distance per battery charge and the recharging time for a long-distance trip. Both criteria can be influenced by the voltage level of the traction system.

A higher system voltage of 800 V instead of the common voltage level of 400 V allows faster recharging of the battery (High-Power Charging, Super-Fast Charging) at constant cable cross sections.

State of the art silicon insulated-gate bipolar transistors (Si-IGBT with diode) used as switching components in the inverter, show efficiency disadvantages for a voltage level of 800 V because the switching losses in the inverter increase too much. To use the higher voltage level properly, a more efficient switching technology is required, see **Figure 1**.

In combination with silicon carbide metal-oxide-semiconductor field-effect transistors (SiC-MOSFETs) the higher voltage level can be applied in an efficient way with high switching frequencies and high voltage slew rates (dU/dt).

More frequent switching reduces the harmonic losses of the electric motor. SiC therefore is a key technology on the way to higher system voltages.

If the optimal balance between the two opposite-running loss curves of the electric motor and inverter can be found, an efficiency increase of 4 % to 8 % is possible in the WLTP on system level (800 V Si system compared to an 800 V SiC system). The efficiency describes the ratio of energy stored in the battery and the energy used to generate traction. A better efficiency results therefore in a greater range with the same battery capacity, or constant range with reduced battery capacity. The efficiency increase is therefore the biggest measure to optimize the costs of BEVs. The significant additional costs of the SiC technology are economically attractive on system level, as they can lead to even greater battery savings depending on the drive concept.

Vitesco Technologies is developing a modular inverter concept for the transition of 400 V to 800 V. The technical platform for this development is the 4th generation of the highly integrated electrified axle drive EMR4 (Electronics Motor Reducer Generation 4). The EMR4 axle drive is a further development of the EMR3 which is now produced in large scale series production in China. The EMR3 is integrated into several vehicles of European and Asian OEMs.

The power electronics (inverter) of the EMR4 is based on the fourth generation of power electronics (EPF 4.0). Vitesco Technologies can use its broad and long-term experience in the development of inverter technologies to realize an inverter concept with low stray inductances and optimized dU/dt. The current development of the highly efficient power electronics for an 800 V traction system with SiC MOSFETs will be realized by an extension of the EPF 4.0 concept.

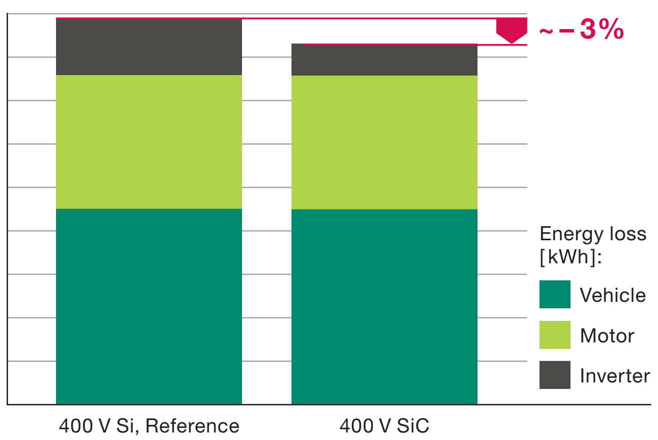

Figure 1: More efficient switching of a SiC compared to Si inverter at a voltage level of 400 V with same switching frequency (10 kHz) and voltage slew rate (5 kV/us).

2 IMPACT OF SWITCHING FREQUENCY AND VOLTAGE SLEW RATE ON SYSTEM LEVEL

During motor operation the inverter transforms DC voltage supplied by the battery into a fast-pulsed voltage. This pulsed voltage causes a harmonic alternating (AC) current. AC phase currents create a rotating electromagnetic field which the rotor follows.

In this way, the pulsed electrical signal increasingly approaches the optimum of a uniform sinusoidal waveform (at 40 kHz and more) and the power losses of higher frequencies decrease. The spectrum of the current becomes "cleaner", which reduces the harmonic losses in form of heat generation.

Figure 2 shows the relation between the switching frequency and the overall losses of the electric motor – $P_{L,EM,total}$ – respectively of the inverter – $P_{L,PE,total}$ – at a certain operation point of the traction system. The motor losses are plotted in green and the power electronic losses in red.

The characteristic curves describe the theoretical dependence of the switching frequency for each parameter: With increasing switching frequency, the harmonic losses of the motor $P_{h,total}$ decrease progressively, so the total motor losses $P_{L,EM,total}$ converge towards the value of iron losses with a purely sinusoidal feed $P_{L,total}$ (dashed horizontal line). The shown graphs are results of high-resolution FEM simulations of the electric motor. The accuracy of the frequency dependent power losses at the grey marked frequency area is lower than of the relevant frequency areas smaller than 20 kHz because of the small simulation step size of 5 microseconds.

The inverter losses $P_{L,PE,total}$ consist of conduction $P_{L,cond}$, and switching losses $P_{L,SW}$. The switching losses increase linearly to the switching frequency. At the same time, the conduction behavior of the semiconductor remains unaffected by the switching frequency. As a result, the overall losses of power electronics are expected to increase linearly with increasing switching frequency in the same way as the switching losses increase, see **Figure 2**.

The basis is an 800 V system with SiC MOSFETS used in the inverter. The characteristic curves in **Figure 2** show the key role of the SiC technology in the power module of the inverter as an enabling factor of highest system efficiency. **Figure 2** shows furthermore that the optimal switching frequency at system level must be defined as influence factor of an increasing efficiency (equilibrium point).

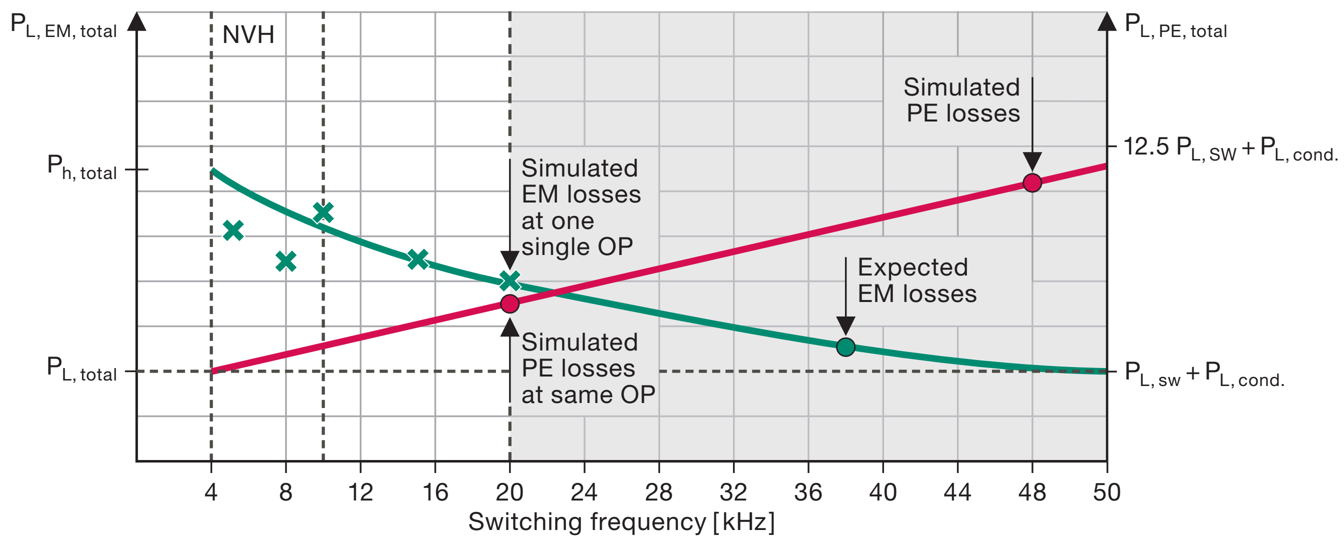

Figure 2: Overall motor and inverter losses as function of the switching frequency at a certain operation point.

The full potential of the SiC inverter technology is based on the possibility of 10 times higher switching frequencies and voltage slew rates compared to a Si inverter. **Figure 3** demonstrates the influence of the voltage slew rate (du/dt) on the inverter losses. The current development of the highly efficient 800 V traction system with SiC MOSFETs investigates how the potential of the SiC technology can be used without unwanted interreferences (see chapter 3 and 4).

To use the full potential of the SiC technology, the electromagnetic compatibility (EMC) as well as the noise vibration harshness (NVH) behavior of the system at high switching frequencies and voltage slew rates must be considered. As shown in **Figure 2** especially lower switching frequencies have a critical influence on the NVH behavior. In contrary to the EMC where higher switching frequencies cause more interferences and as a result the shielding concept must be eventually redesigned.

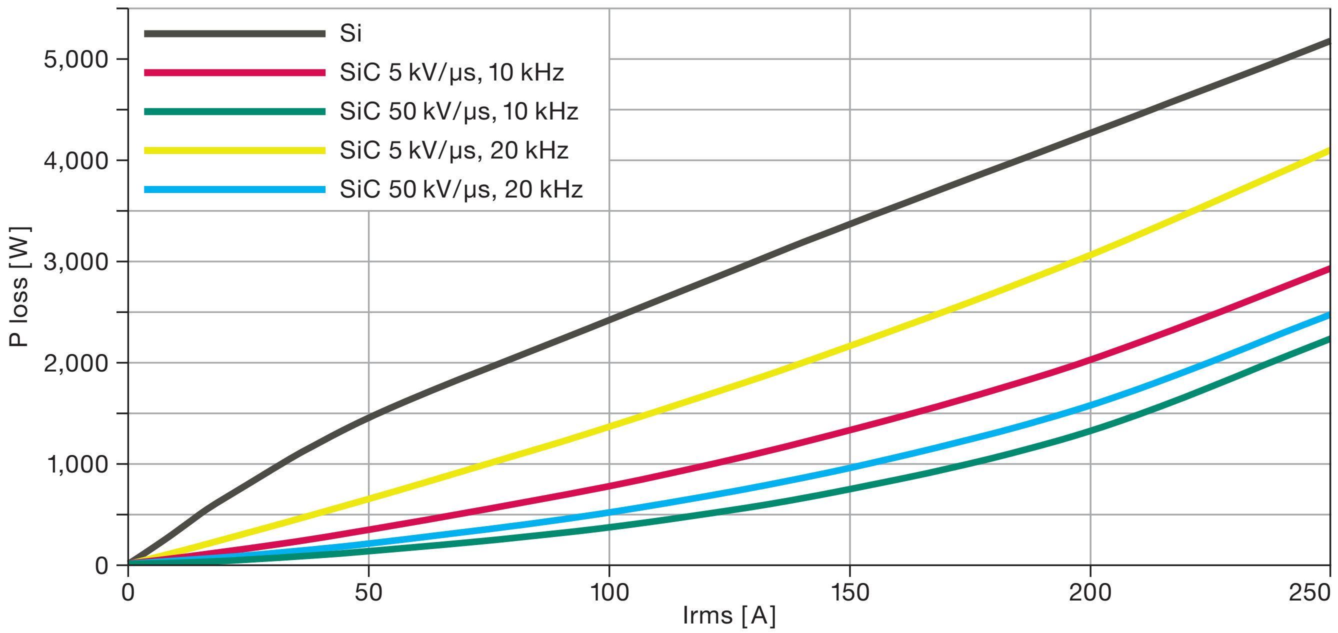

Figure 3: SiC inverter power losses at 10 kHz and 20 kHz, with 5 kV/µs and 10 kV/µs in comparison to the overall losses of Si for 10 kHz and 5 kV/µs.

3 IMPACT ON THE INVERTER

Today's state of the art 400 V Si-IGBT inverters operate at switching frequencies of 8 to 10 kHz. The voltage slew rates are typically up to 5 kV/µs.

Figure 4 shows the differences of single inverter systems (Si/SiC) and the resulting losses at different output powers. The cumulated overall power losses are split up into switching and conduction losses.

The differences between the total power loss at 800 V of conventional Si technology and SiC technology are significant. The graph confirms that an increased voltage of 800 V can only be used in an energetic way with SiC semiconductors.

The decisive factor for assessing an inverter is the efficiency that the drive shows in the WLTP cycle (Worldwide harmonized light vehicles test procedure). **Figure 5** illustrates the influence of the inverters on the efficiency of the drivetrain in the WLTP. The yellow segment of the bars shows the advantage of 800 V SiC over an 800 V Si solution – although only a switching frequency of 10 kHz and a voltage slew rate of 5 kV/µs are applied in both cases. An inverter equipped with SiC semiconductors could possibly operate at higher frequencies and slew rates (typical values: switching frequency: 10 ... 40 kHz, du/dt: 5 ... 50 kV/us). The second bar on the left side of **Figure 5** shows how the losses would develop if a Si inverter would be used for the 800 V system.

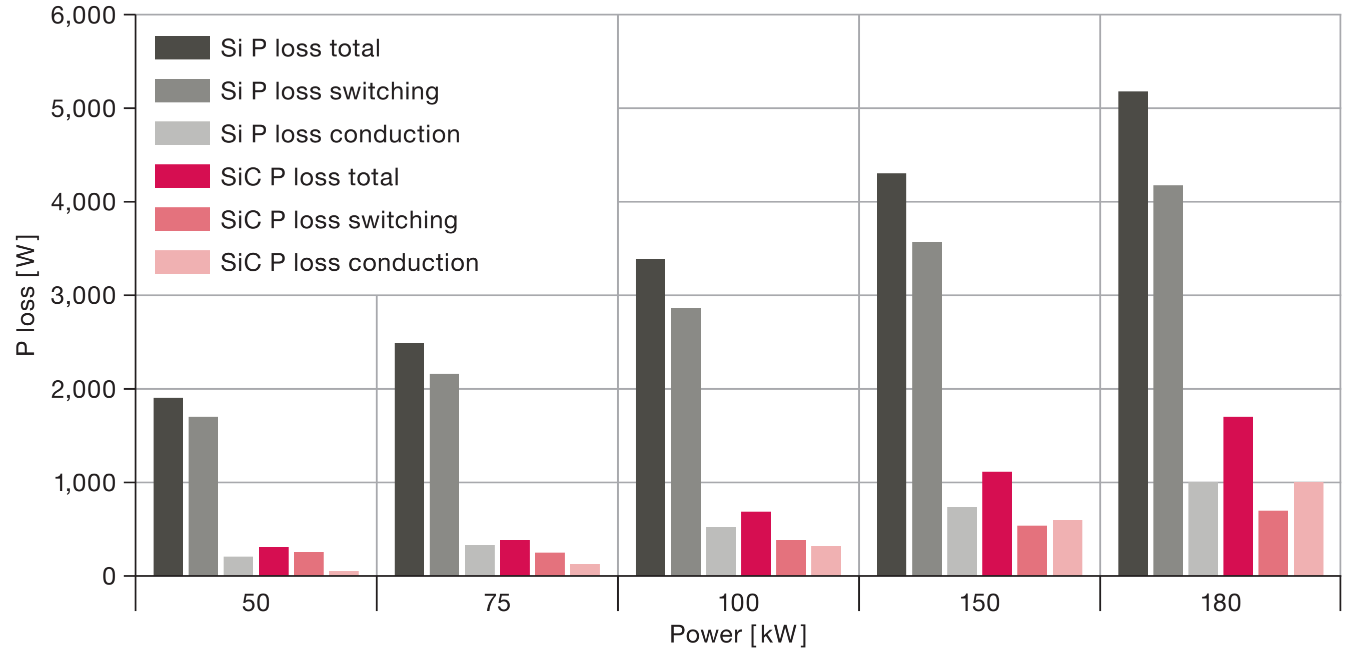

Figure 4: Power losses for different inverter concepts as function of the output power.

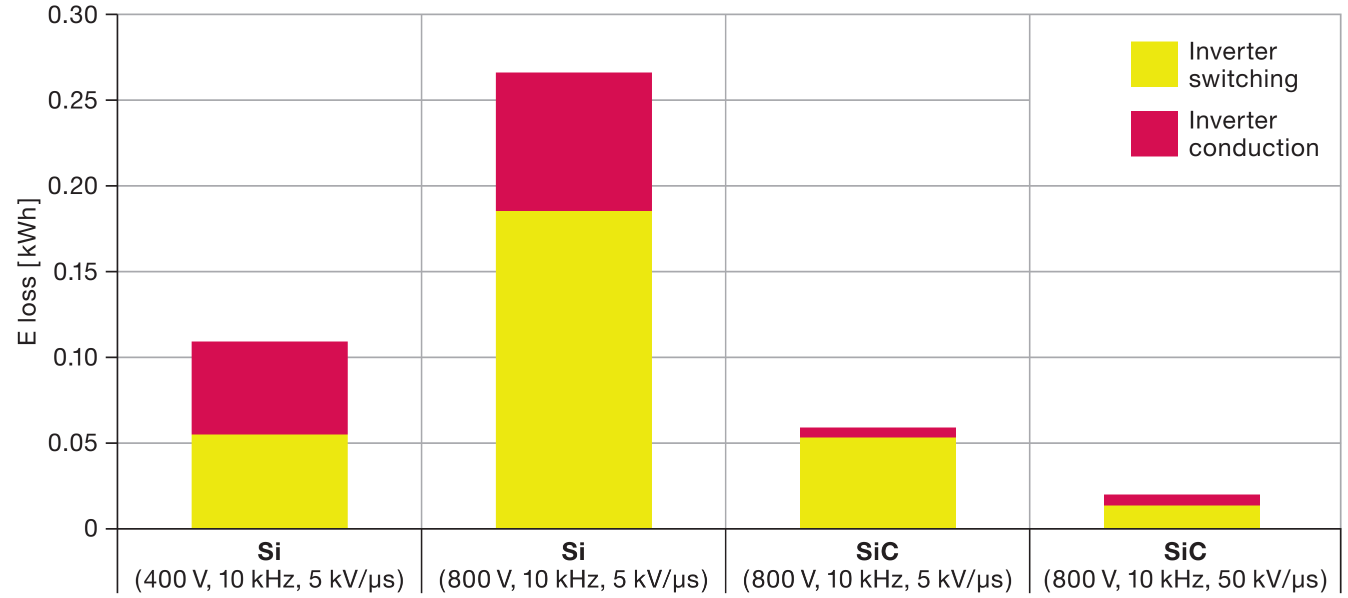

Figure 5: Impact of inverter concepts on power losses in the WLTP cycle.

The higher efficiency of the SiC technology shown for different aspects in **Figure 1 to 5** is based on the high charge carrier mobility in the material matrix of the carbon atoms embedded in the silicon. Due to the low electrical resistance the generation of heat losses in the SiC semiconductors is low. This allows higher switching frequencies, a compact assembly space and the reduction of cooling capacity demand in the power module. SiC semiconductors therefore require a smaller active area than Si semiconductors.

3.1 ADVANTAGES OF HIGHER CONDUCTIVITY

In today´s automotive traction inverters (400 V system voltage level and up to 10 kHz switching frequencies) low-loss Si IGBTs with an additional diode are used (free-run respectively backflow into the battery at recuperation mode). The bipolar transistors with reverse voltages between 650…750 V require a complex control but work as "perfect switches" because of the high efficiency at nominal voltages.

MOSFETs (Metal-Oxide Semiconductor Field Effect Transistor: simply put: voltage controlled resistances) are easier to control. Equipped with silicon semiconductors they show a higher electrical resistance (R) during the switching process (R at Drain/Soure On = R_{dson}) than Si IGBTs.

At 400 V, the higher Si MOSFET power losses already have an important influence, at 800 V they become the exclusion criterion (see **Figure 5**). The higher the blocking resistance of the Si MOSFET, the higher its R_{dson}. Above a voltage level of 600 V, this electrical behavior has a relevant effect on the overall efficiency. Additionally, the increased cooling effort at higher voltages has to be considered.

MOSFETs with SiC technology in 4H substrates (Tetraedermatrix with extreme high charge carrier mobility) show especially during the switching process a higher efficiency than those with Si technology. The advantage of the lower R_{dson} is the main reason for SiC MOSFET semiconductors in 800 V inverter concepts.

The wider band gap and the higher break down voltage on a low surface resistance of SiC, allows to switch high voltages with high voltage slew rates. Because of the much lower R_{dson} the switching losses remain at a low level for higher switching frequencies, see **Figure 6**. Especially at partial load the low conduction losses have a positive impact.

Considering all constraints e.g. connection interfaces of the power module the SiC technology will probably lead to an assembly space reduction of 25…50 % of the volume of the power module.

The higher thermal conductivity of SiC compared to Si provides the possibility of a better transfer of heat losses. At the same time SiC semiconductors can operate at higher temperatures. This results in high power densities which are demanded of the inverter design.

An overall analysis shows, that SiC enables higher inverter efficiencies, reduced switching losses, less assembly space, less cooling capacity, higher operation temperatures and less weight of the power module.

Compared to a 400 V Si inverter a 400 V SiC inverter can be designed more compact. An 800 V SiC inverter instead will require more volume, because of the bigger creepage path and especially because of the bigger intermediate circuit capacitor.

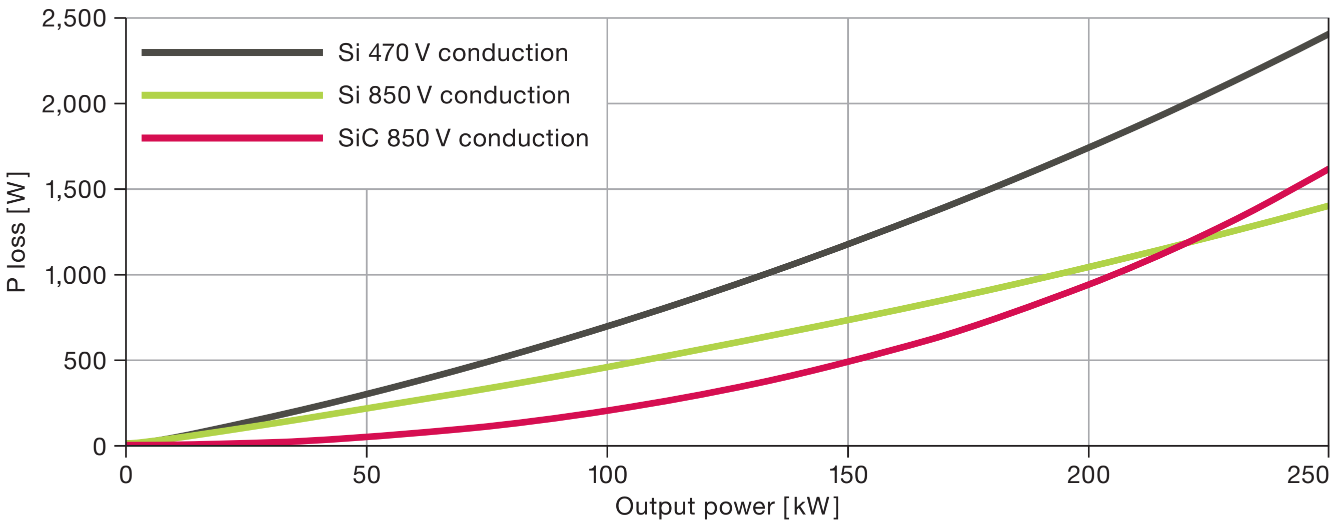

Figure 6: Inverter conduction losses for Si IGBT 400 V, Si IGBT 800 V and SiC MOSFET 800 V.

In principle, the advantages of the SiC technology can also be used in combination with a 400 V system, but then only the efficiency advantage in the inverter can be realized. Additional advantages like the super-fast charging require a higher voltage level. To investigate the potentials under operating conditions, a 400 V SiC inverter prototype is tested in a vehicle. The 800 V inverter with SiC technology is now in the testing phase.

3.2 DYNAMIC ADVANTAGES OF SIC

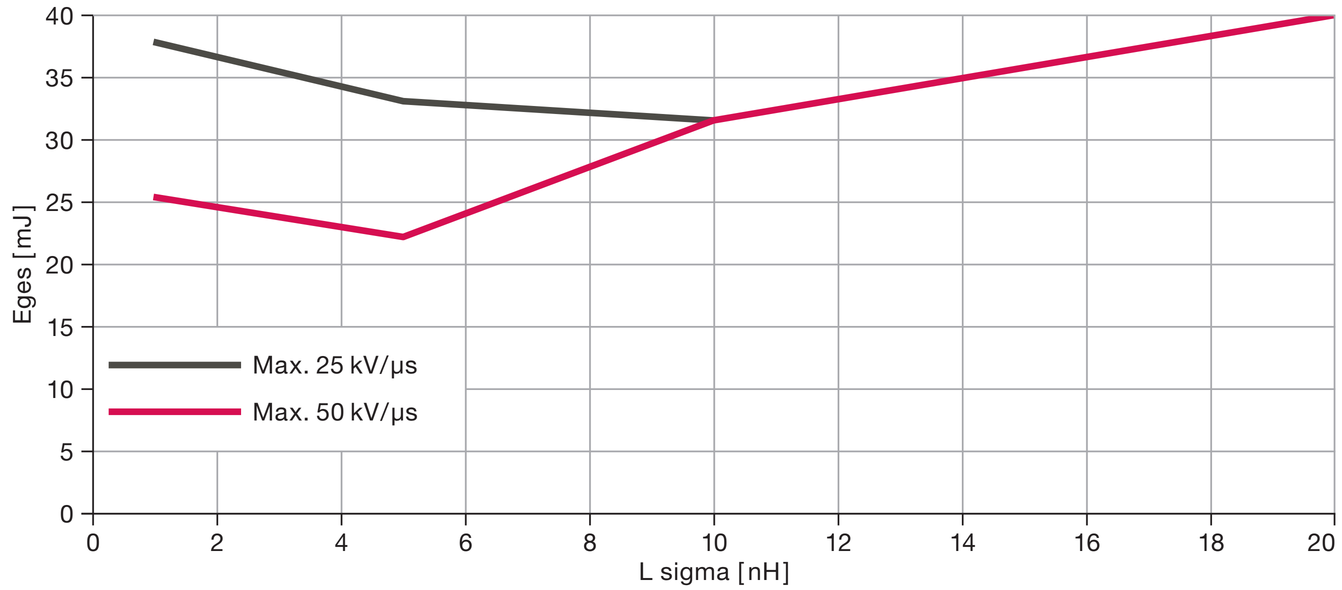

Figure 7: Influence of stray inductance on inverter losses at a certain operation point during switching.

As shown in **Figure 7** the switching losses can be reduced in SiC semiconductors by increasing the voltage slew rate dU/dt. The technology provides big potentials compared to Si because higher slew rates with adjusted stray inductances in the commutation circuit reduce the power losses. This requires the optimization of the stray inductance in the gate source circuit.

Since a very low stray inductance in the commutation circuit is only relatively cost-intensive to implement, it is part of the optimization at system level to define a balanced dU/dt. The stray inductance will be simulated at a certain dU/dt. In combination with the increase of the switching frequency, the overall power losses can be simulated for a WLTP cycle. In a range of 5…20 kV/µs there should exist a local minimum at which the stray inductance is on a low level and the savings for the WLTP cycle are evident.

3.3 ELECTROMAGNETIC COMPATIBILITY

Switching processes with high frequencies are known to cause electromagnetic signal interferences. For the application of SiC MOSFETs in traction inverters the trade-off between higher switching frequencies and slew rates on one hand and higher shielding and filter effort on the other hand must be investigated. **Figure 8** shows the effect of doubling the switching frequency (10 kHz to 20 kHz) on the interference spectrum and the interference intensity in an exemplary measurement. The intensity of the interferences rises about 6 dB at 20 kHz. Only to increase the switching frequency will not result in an optimal solution. The optimal control parameters for SiC must be investigated. This should lead to a high efficiency with good EMC behavior, acceptable switching losses at possible switching frequencies and optimal efficiency increases in the motor.

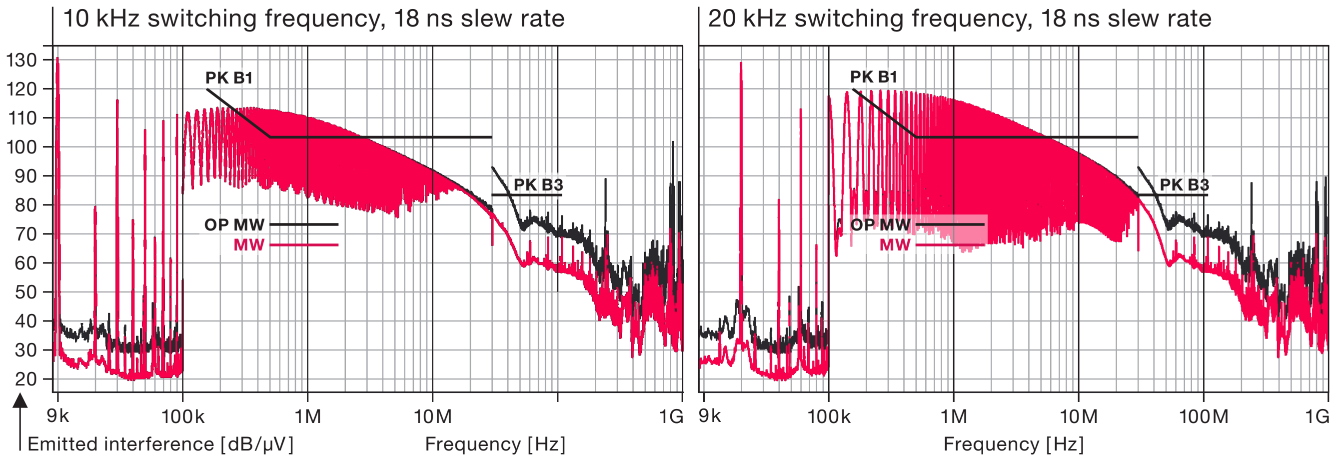

Figure 8: Influence of the inverter switching frequency on the EMC interference spectrum.

4 ELECTRIC MOTOR DESIGN

The basis of the development of the integrated highly efficient axle drive for 800 V applications is the electric motor of the EMR3 which is produced in large scale series production. The compact unit consisting of an electric motor, an inverter and a reducer weights under 80 kg, reaches performances up to 150 kW and motor torques up to 310 Nm. The EMR3 is powered by a permanent magnet synchronous motor (PSM) which operates under currents up to 510 A supplied by a 400 V Si IGBT inverter. A frontally mounted 2 stage transmission adjust the motor speeds from 14,000 rpm to the speed required at the wheels of the vehicle.

The axle drive EMR4 will have a larger scalability than the EMR3 by more possible combination of subcomponents (as the 800 V inverter option). Besides this the interconnection design will be more standardized and the scalability of the interconnections will be increased. Especially for lower power applications the assembly space will be reduced.

Compared to the EMR4 base design the coil number of the 800 V derivate has been doubled by changing the interconnection design.

The new axle drive will be developed for power segments between 60 and 180 kW. To realize this the design has changed in a way that the power electronic of the EMR4 is placed at the opposite end face of the transmission. A broad vehicle portfolio can be equipped within one drive module by extension of the performance scalability.

4.1 EFFICIENCY INCREASE IN THE ELECTRIC MOTOR BY USING SIC TECHNOLOGY

The power loss analysis in chapter 3 shows that SiC MOSFETs enable faster and more frequent switching with the same cooling capacity. A higher switching frequency can increase the efficiency of the electric motor.

More frequent switching, respectively a higher switching frequency leads to a reduction of the harmonic currents. As a result, the harmonic input power supplied by the inverter can be reduced by increasing the switching frequency.

Figure 9 illustrates the aspect described in the section before in a power flow diagram. The usual power flow (grey) from the input power, via air gap power, to the mechanical output power on the shaft. The stator and later the rotor power losses are transferred via heat dissipation.

The harmonic input power which is transformed completely into heat and doesn´t contribute to the mechanical power is marked in red. The harmonic losses of an 800 V electric motor can be reduced with SiC technology.

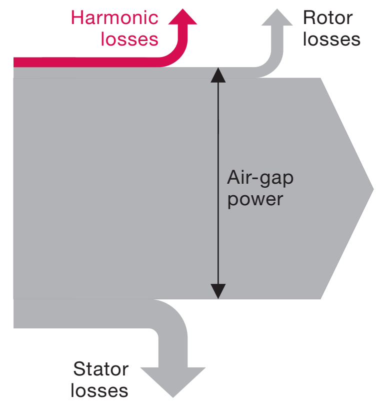

Figure 9: Power flow diagram of a PSM considering the harmonic power losses.

4.2 DESIGN PARAMETERS OF AN 800 V ELECTRIC MOTOR

Variable frequency fed electrical machines are known to be stressed more than machines ran by a constant speed, respectively supplied by a sinusoidal constant frequency. **Figure 10** shows the additional impacts on the motor caused by a fast switching inverter. The application of the 800 V SiC technology requires a closer look on the insulation system and the bearing currents of the motor.

Although the high-frequency voltage pulses with very short rise times supplied by the inverter create the basis for an efficient system, these pulses increase the stress on the motor. Especially at high output powers, when the highest slew rates can be observed.

The task of the system design is to find the right balance between low harmonic losses and increased requirements on the insulation system and the service lifetime of the electric motor due to high switching frequencies and voltage slew rates. The optimal balancing of these two aspects is important for the design of the SiC traction system.

The insulation system of the motor must withstand overshoot voltages which occur as a result of the voltage level of 800 V in combination with high switching frequencies and dU/dt's.

The test voltage for those systems also increases. The cable length between motor and inverter output terminals must be designed as short as possible to prevent additional voltage overshoots as a result of reflected voltage waves.

The reflection coefficient r and the motor impedance Z in **Figure 10** illustrate this aspect. By choosing the optimal dU/dt, and hence the optimal rise time, it shall be considered that the critical cable length is directly linked to the rise time. Due to this relation the voltage rise time cannot be chosen as high as desired.

This implies that for the development of an 800 V derivate of the EMR4 the behavior and the service life of the insulation system have to be investigated.

High voltage peaks can cause partial discharges, because the peak voltage, for example between a conductor and the lamination stack, reaches a level that electrical charges can breach the insulation system at weak spots. This causes short time breakdowns of the insulation system. The temporary generated currents create permanent stress on the insulation system. As a result, the system heats up and ages. It is important to know the effect of the voltage pulses on the service life. Corresponding partial discharge measurement results are used for the design of the insulation system.

Moreover, there exist mechanisms in speed regulated motors that cause high frequent bearing currents under inverter operation. These include circular currents (shaft, bearing, stator, stator housing, bearing, shaft) as a result of potential differences at the end of the motor shaft, as well as capacitive bearing currents (also called dU/dt-currents) and electrical discharge machining (EDM) currents as a result of the

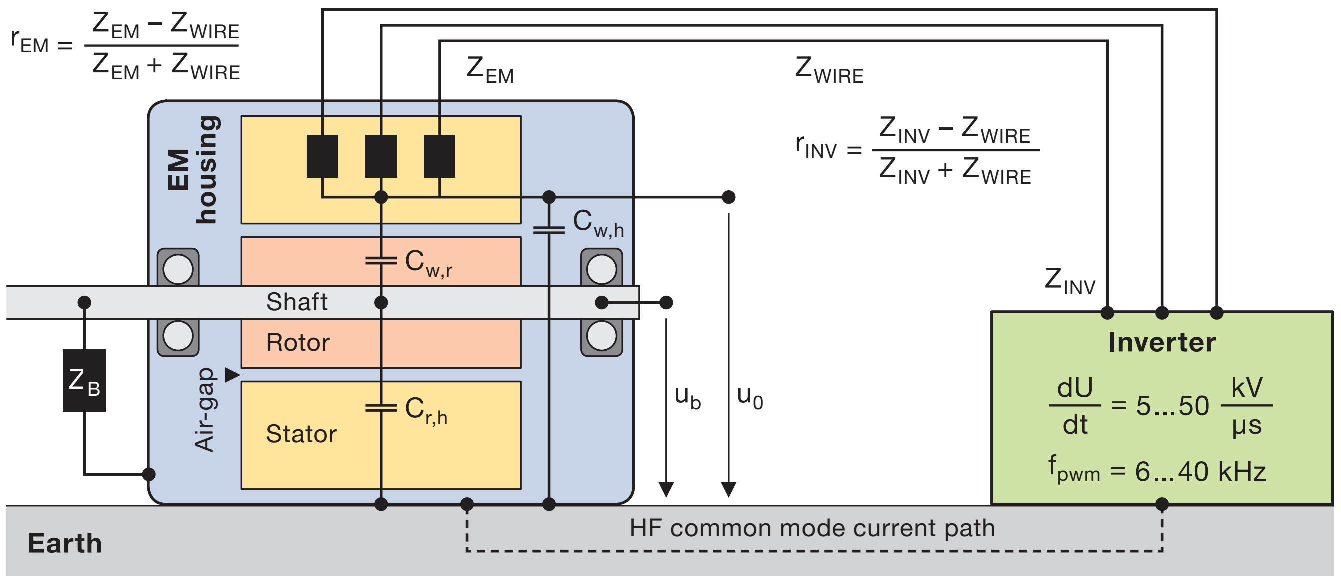

Figure 10: Electrical equivalent diagram representing significant parasitic effects.

temporal change of the common mode bearing voltage UB. EDM currents occur as high amplitude discharge current peaks when the lubricating film capacity of the bearing lubricant locally collapse. In the automotive sector, EDM currents are regarded as relevant for practice applications. The ratio of the common-mode bearing voltage UB to the common-mode voltage U0 – the so-called bearing voltage ratio (BVR) – can be used for the first estimation of the expected EDM currents. In a high-resolution measurement of the bearing voltage at different operation points characteristic voltage peaks can be observed indicating relevant discharge currents. The critical operation points can be identified with respect to the service life of the bearings. After identifying the potential points, continuous tests with a high proportion of these operation points are carried out and the service life of the bearings will be evaluated.

As shown in **Figure 10**, the bearing voltage U_B is connected to the common mode voltage U_0 via a capacitive voltage divider. It consists of the parasitic motor capacitances (winding housing $C_{w,h}$, winding rotor $C_{w,r}$ rotor housing $C_{r,h}$) and the bearing impedance Z_b. The equivalent circuit diagram shows measures to prevent EDM currents, such as the use of shaft grounding, electrostatic shielding of the stator winding heads or the use of control methods for minimizing the common mode voltage U_0.

5 SYSTEM ANALYSIS

The previous chapters show the influences and possibilities of SiC technology on component level. The next step is to bring the benefits together in an optimized traction system in terms of cost and efficiency, but also considering NVH and EMC behavior.

5.1 PROCEDURE TO TRANSFER SINGLE CHARACTERISTIC POINTS ON THE WLTP

In order to evaluate the effectiveness of the technology in the WLTP from measured values in a torque-speed characteristic diagram, the points in the WLTP with maximum accumulation were chosen as measurement points for the test campaign. **Figure 11** shows on the example of a D-segment vehicle with the EMR4 axle drive the histogram values. 35 operation points have been defined and were measured at different switching frequencies in combination with different voltage slew rates on a motor test bench.

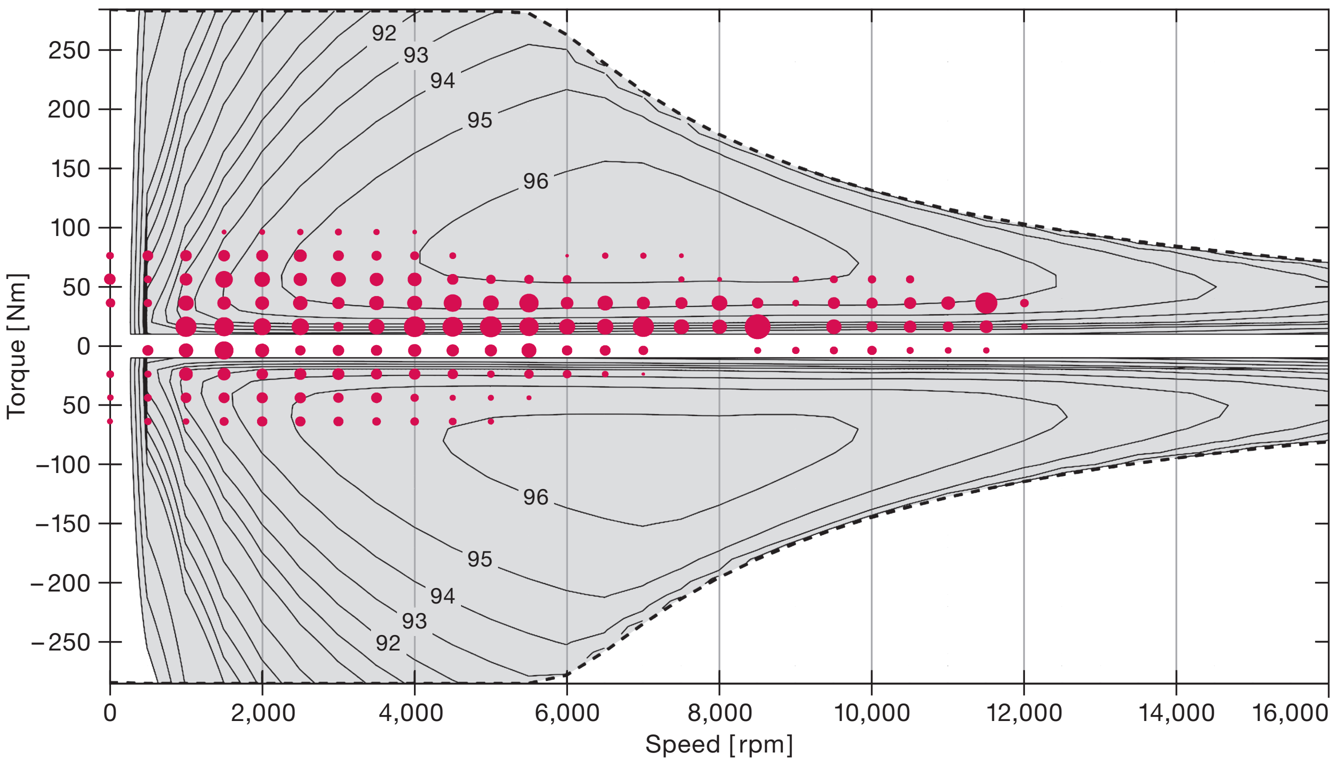

Figure 11: WLTP histogram for a D-segment vehicle.

5.2 DISCUSSION OF THE TEST RESULTS

The evaluation of the measurement results revealed two key findings which are decisive for the further development of the SiC technology. For the basic measurements a high and a low voltage slew rate was implemented in the inverter. At certain operation points, the high slew rate corresponds to 10 kV/µs, the low to 5 kV/µs.

Figure 12 shows the differences of power losses on component and system level at one operation point in the medium speed range with low torque. The power losses of the inverter are expected to increase over the switching frequency, and no difference between 5kV/µs and 10kV/µs can be detected within the measurement accuracy. This is due

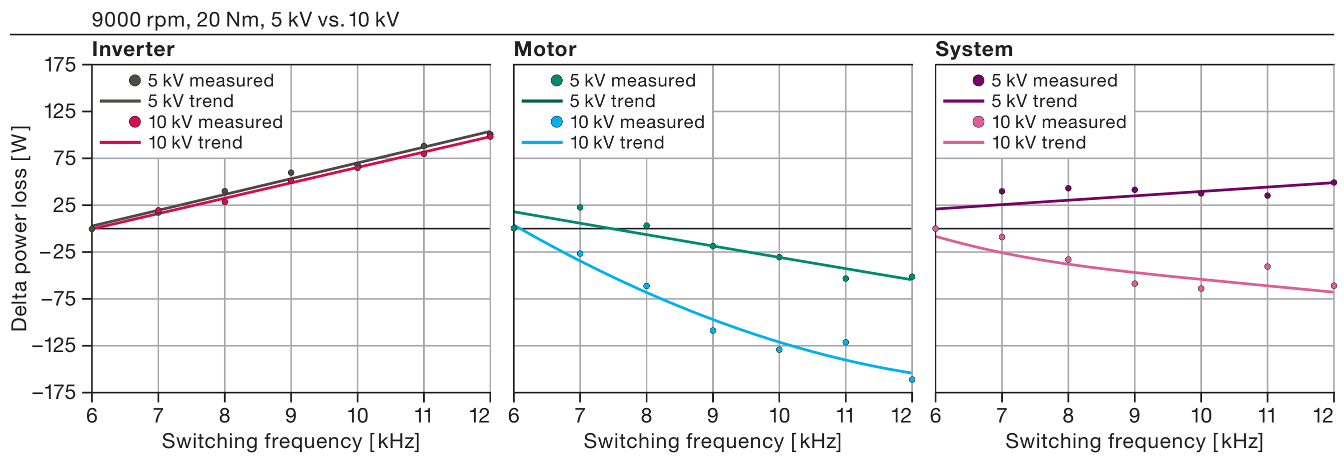

Figure 12: Test results of the components and system power losses at 9000 rpm and 20 Nm.

to the operation point-dependent slew rate, which has only low effects at low loads. The motor, on the other hand, shows a decrease in power losses with increasing switching frequency, but also reacts to the higher voltage slew rates of 10 kV/µs. This advantage compensates the higher inverter losses on system level occurring as a result of the higher switching frequency. Overall it represents an improvement in the efficiency.

The advantage of 10 kV/µs on the inverter level for higher currents can be observed in Figure 13 as the overall inverter losses increase with increasing inverter currents (respectively inverter output power). The motor performance is likely unchanged compared to the performance measured at low speeds, but only minor improvements are observed at system level at higher switching frequencies above 8 kHz. The behavior observed in **Figure 13** shall be transferred to all operation points in the characteristic curve by adjusting a higher voltage slew rate.

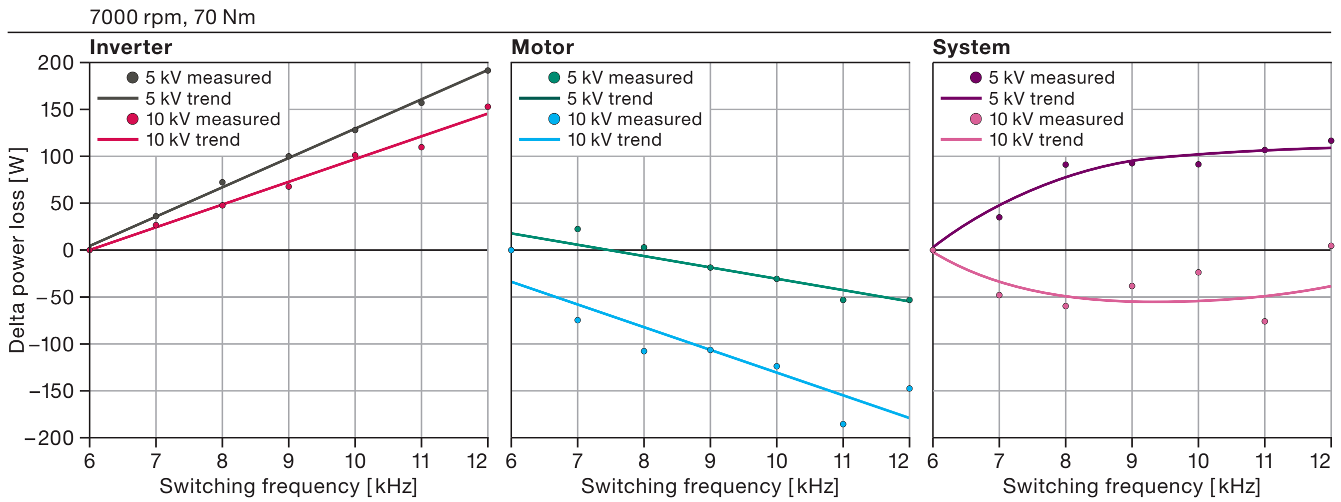

Figure 13: Test results of the components and system power losses at 7000 rpm and 70 Nm.

5.3 EVALUATION OF THE ENERGY SAVINGS IN THE WLTP

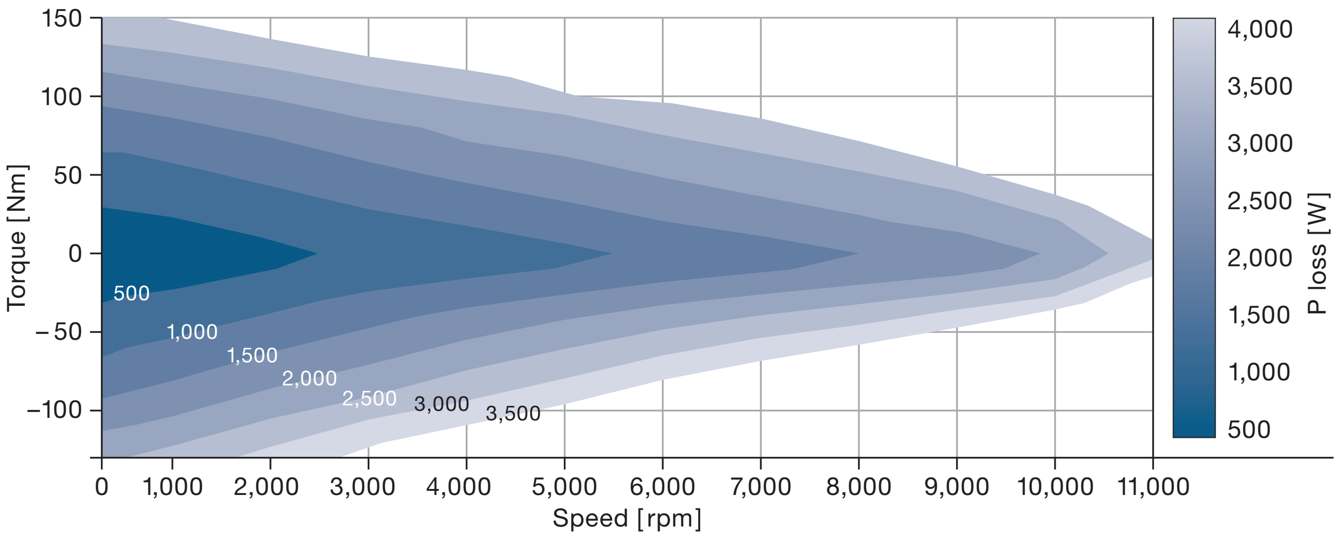

Figure 14: Interpolation of measured power losses at 12 kHz/5 kV/µs for the WLTP relevant power segments.

The measured values were used to calibrate the simulation models of the inverter and the electric motor in order to identify the overall efficiency in the WLTP cycle and to simulate other consumption cycles in the future. In order to provide a first indication of the efficiency potentials of the SiC technology, the measured losses on system level have been transferred to a characteristic diagram. A sufficiently accurate grid has been established by appropriate interpolation methods to represent the entire cycle in a drive simulation. **Figure 14** shows the characteristic system diagram as an example for a voltage slew rate of 5 kV/µs and a switching frequency of 12 kHz.

Figure 15 shows the results for a D-segment vehicle in a WLTP cycle between the limits of 5 kV/µs (6 and 12 kHz) and 10 kV/µs (6 and 12 kHz). An increase of the PWM frequency in the WLTP leads to an increase of the efficiency of the motor. In addition, it confirms that the increase of the slew rate of the inverter output voltage causes a reduction in the electrical losses in the inverter both for 6 kHz and for 12 kHz. In accordance with **Figures 14 and 15**, the calculated loss reduction values in the inverter are lower than the development target. Thus, the measured increase in efficiency and the subsequent transfer to the WLTP showed that significant advantages can be achieved in the WLTP by reducing switching losses due to silicon carbide semiconductors and a loss-optimized frequency. The next step of the optimization is the increase of the frequency and the voltage slew rate.

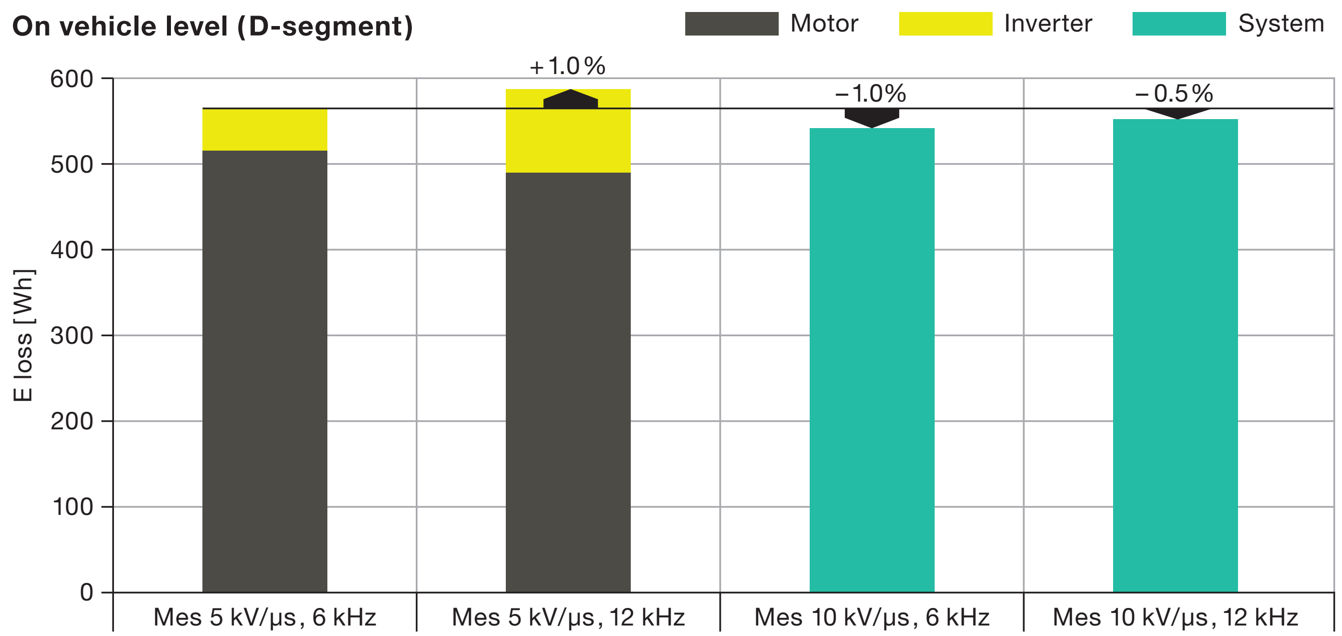

Figure 15: Motor and inverter losses with interpolated characteristic cuves for the WLTP.

5.4 OPTIMIZATION

From the performed investigations it can be deduced that by using silicon carbide semiconductors in the inverter, besides the classic parameters of the control strategy such as modulation method and change of the switching frequency, a new parameter can be used to increase efficiency. The voltage slew rate offers the possibility to apply switching frequencies that were previously not possible. Vitesco Technologies owns with the tool iMCO [1] the capability to find the best balance between the relevant parameters in a multi criteria optimization. With the results a control strategy can be developed which uses the full potential of silicon carbide semiconductors in the traction system in a potential serial production.

6 SUMMARY AND OUTLOOK

Due to the high potential of increasing the efficiency the use of the semiconductor material silicon carbide faces a breakthrough for high-voltage automotive applications. The system optimization provides solutions which achieve the maximum efficiency of inverter and electric motor. All conclusion on certain operation points were additionally presented by their influences on the effectiveness in the WLTP, using the example of a D-segment vehicle.

Silicon carbide is known to have a higher conductivity in the switched state than current standard solutions with silicon IGBTs. On vehicle level, a system efficiency increase up to 3% is possible for an 800 V voltage level with SiC MOSFETs compared to Si IGBTs.

In addition to this advantage, silicon carbide provides the possibility of a significant increase in the voltage slew rate at the inverter output > 20 kV/µs (theoretically), which cannot be represented by silicon semiconductor solutions today. A further efficiency increase of 2–4% compared to Si IGBTs can be represented in the inverter at the same switching frequency. This has been proven for certain operation points. Nevertheless, the transfer of the full potential of the optimal switching frequency and voltage slew rate in the WLTP requires further investigations.

By increasing the switching frequency, the electric motor shows a higher efficiency due to the lower harmonic currents and the associated lower dynamic losses.

An increase of the switching frequency leads generally to an increase of the switching losses in the inverter. A solution with silicon carbide semiconductors makes it possible to reduce the overall switching losses as a function of the inverter switching frequency by increasing the voltage slew rate. This effect can be used positively to increase the efficiency of the inverter and electric motor system. Overall, the frequency increase in the electric motor results in a further efficiency increase of 1–2%. To reduce the efficiency disadvantages the voltage slew rate must be adjusted as high as EMC constraints allow it. The system optimization leads to efficiency improvements in total of 6–8% for a voltage level of 800 V by using SiC instead of Si semiconductors. Even with slight increases of the switching frequency and voltage slew rates 60% of the possible potential efficiency increase can be realized. The increase of the switching frequency up to 20 kHz and the voltage slew rate up to 15 kV/µs is the next step of the development process. This does not represent the maximum possible values that can be obtained with silicon carbide, but the parameters are possible in large-scale series production considering the insulation and EMC behavior.

The inverter developed at Vitesco Technologies is optimized in a modular design for the use of silicon carbide and for maximum efficiency. The key parameters of the semiconductor and the module design were identified and adapted in a system wide optimization.

The optimum range of the stray inductance could be identified as key parameter of the optimization in order to minimize the switching losses at a certain switching frequency. To reach the efficiency increase of the SiC technology besides the operation point-dependent adjustment of the voltage slew rate and the switching frequency a software and application extension must be applied.

The described system optimization of the electric motor and the inverter including the control strategy and the semiconductor material can be used to provide solutions for 800 V systems. This will make a further contribution to increasing the efficiency of electric drives and at the same time increase the efficient usage of resources. Vitesco Technologies attaches great importance to the use of the SiC technology in order to implement these objectives in large-scale series production with customers and strategic suppliers in the short term.

Literature:

[1]
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