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Low inductive power module design for tractive systems

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Abstract

This paper presents a novel low inductive power module design with integrated common mode EMI shielding, called LinkPack. The 600 V / 200 A modules can be realised as full SiC, hybrid or Si modules. The new design is optimised for high switching frequencies of 20 kHz and more and low stray inductances to increase switching speed and simultaneously not enlarge turn-off over-voltage. In order to achieve a low inductive power loop, DC-link capacitors are integrated and the bottom side of used AlN DCB is carrying DC-link GND potential. Measurements reveal a significantly improved switching behaviour achieved by the new design.

Keywords: electric drive, inverter, optimization, powertrain, semi-conductor

1 Introduction

Modern electric traction motors can be typically divided into two different kind of concepts: on the one hand there are motors with very low inductance like some kinds of fractional slot winding machines. This type of machine is used in specific applications, for instance motor sport and aviation. It can provide maximum torque over the whole operation range up to maximum speed. To avoid an unacceptable high current ripple, high switching frequencies are mandatory. On the other hand, there are special motor designs which allow field weakening over a wide range of speed. These designs - inter alia axial and transverse flux motors - often have a high number of poles, so very high electrical fundamental frequencies are required to operate these motors.
So most of this modern concepts demand significantly higher switching frequencies for the power electronics compared to conventional electric machines. To increase the switching frequency of standard hard-switching 2-level inverters it is important to significantly reduce the losses per switching operation by improving the switching behaviour of the devices [1, 2, 3]. New SiC power semiconductors are highly suitable for this application [4] but also very expensive. Regarding cost sensitive applications, improving switching behaviour of Si-IGBTs / SiC-diodes hybrid modules and Si-IGBTs / Si-diodes modules is desirable as well. The new module design has to be optimised for low stray inductances to increase switching speed and simultaneously not enlarge turn-off over-voltage. Furthermore, high dV/dt switching gradients negatively affect the EMI, so the module design has to reduce common mode noise level to comply with EMC standards.

2 Module Design

Using a novel module design, an ultra-low inductive half-bridge power module is designed and manufactured. It carries an integrated DC-link and fast switching 1200V SiC-Mosfets. Furthermore, it is possible to equip Si-IGBTs / SiC-diodes or Si-IGBTs / Si-diodes instead of wide bandgap semiconductors. The load current rating is 200 A rms. Film capacitors are used for DC-link of the new module. However, it is possible to equip additional ceramic capacitors underneath the film capacitors which allows an ultra-low power loop inductance of 1.6 nH.

Fig. 1 depicts the LinkPack module design. The copper layer of AlN-DCB-bottomside carries the DC-link GND which enables a low module stray inductance and an integrated common mode EMI shielding [5]. Since DC-link GND is part of the high voltage system it has to be separated from the GND of the heat sink. So an additional insulation layer is required, which increases the thermal resistance of the cooling path. Furthermore, a load current sensor, screw terminals to connect DC-source and load and a 3D-printed press down frame are mounted on the DCB. Last-mentioned serves as barrier for silicone dielectric gel and further hosts pressure springs which press the module down to the heat sink.

The LinkPack module's nominal output current can be easily modified by varying the number of equipped parallel power semiconductors. Other novel module designs [1] restrict a further scaling up. In comparison to this designs, the number of semiconductors of the LinkPack design can be increased or decreased without affecting its switching behaviour or leading to an uneven current distribution. Therefore, only the mechanical dimensions of the used DCB have to be adapted.

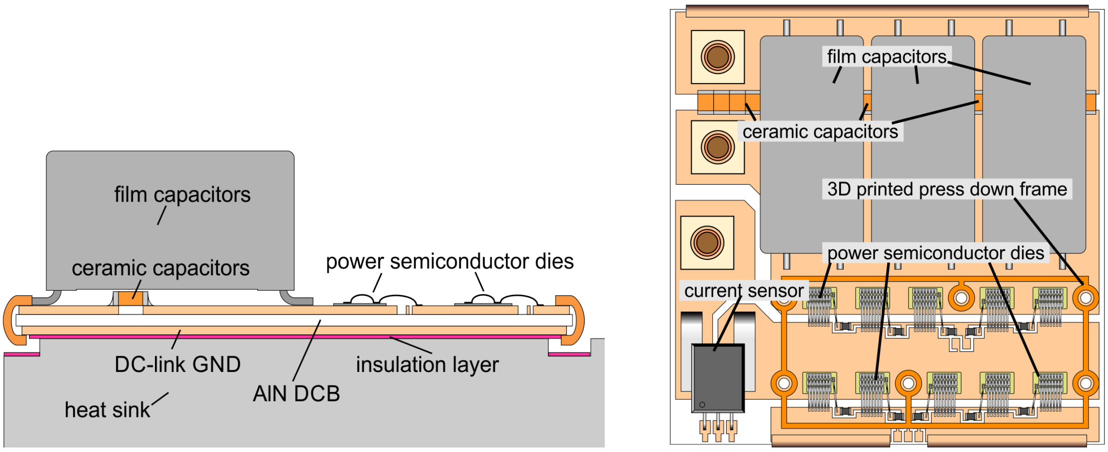

Figure 1: LinkPack module design. Left: Cross section of module. To allow better visibility of the two-sided structure, the illustration is spread in y-dimension. Right: Top layer of the LinkPack module with mounted 1200V SiC-Mosfets, film and ceramic capacitors.

3 Module stray inductance

The power loop stray inductance of the module can be calculated by following formula for inductance of a long coil with relative permeability approximately one.

$$L_\sigma = \frac{\mu_0 \cdot A}{l} \tag{1}$$

Taking mechanical dimensions of the module like thickness of the AlN DCB and bond loop height into account, it provides 1.35 nH. This calculated value has to be validated. Therefore, modules were equipped with Mosfets and various kinds of DC-Link capacitors. Film capacitors with an overall capacitance of 45 μF respectively ceramic capacitors with an overall capacitance of 2.5 μF were attached to two LinkPack modules, as depicted in Fig. 2. Furthermore, ceramic capacitors from TDK [6] with an overall value of 500 nF were mounted on a third module.

The capacitors of each module were charged and separated from voltage source, followed by short-circuiting the module with the Mosfets. A distinct voltage oscillation can be observed. The oscillation circuit consists of DC-link capacitance and overall power loop inductance, composed of capacitor's ESL and module-only stray inductance. Fig. 3 depicts voltage oscillations of short-circuited modules with A: 2.5 μF ceramic capacitors, B: 500 nF TDK ceramic capacitors and C: film capacitors. A resonance frequency of 2.5 MHz with 2.5 μF ceramic capacitor module and a frequency of 5.6 MHz with 500 nF ceramic capacitor module lead to an determined overall power loop inductance of 1.6 nH. Subtracting the specified ESL of the ceramic capacitors [6] results in a module-only stray inductance of 1.35 nH, which validates the calculated value using the formula for the long coil. Fig. 3C clearly shows a significantly damped voltage swing of the film capacitors module, originating from a very pronounced ESR of the film capacitors. A low total ESR is mandatory to correctly determine the resonance frequency of the oscillation circuit. Therefore, the method of observing the resonance frequency is not suitable calculating the film capacitor's ESL. As an alternative, the impedance curve of one used film capacitor was measured. The result is depicted in Fig. 3D. ESL and ESR were determined by approximating the measured impedance course using a simple simulation model. Therewith, one film capacitor's ESL can be determined by 19 nH, resulting in a total film capacitors ESL of 6.3 nH. The achieved commutation loop stray inductance of 7.65 nH (module with film capacitors) respectively 1.6 nH (module with additional ceramic capacitors) is significantly lower compared to conventional power module set-ups which typically show a module-only stray inductance of 15 nH to 20 nH [7, 8, 11]. For the whole commutation circuit, one has to add the ESL of the applied capacitor module with 15 nH to 20 nH, so 30 nH to 40 nH are typical values.

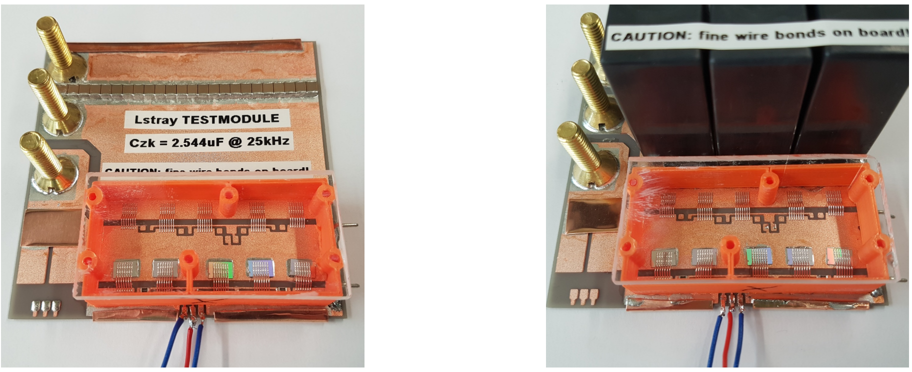

Figure 2: LinkPack test modules equipped with 2.5 μF ceramic capacitors (left) and 45 μF film capacitors (right).

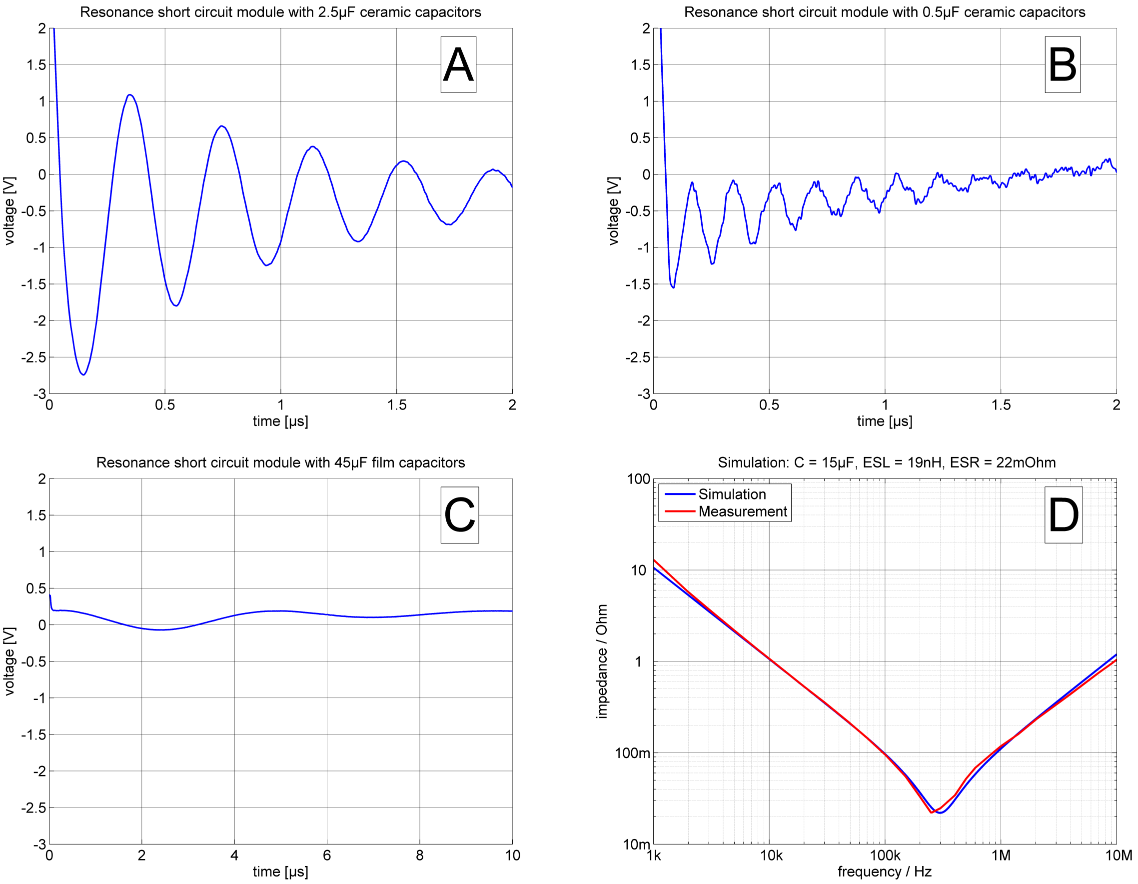

Figure 3: Determination of LinkPack module's stray inductance. Resonance behaviour of LinkPack modules equipped with 2.5 μF ceramic capacitors (A) and 500 nF TDK CeraLink capacitors (B). The resonance swing of the module with film capacitors is significantly damped (C), so the ESL of one film capacitor was determined by measuring its impedance curve (D).

4 Switching behaviour

4.1 Si modules

For first measurements of switching behaviour the ultra-low inductive power module was equipped with Si-IGBTs and Si-diodes (Fig. 4 and 7). Its switching behaviour was compared to a reference Si module SKM200GB12T4 from SEMIKRON [8] with optimized low inductive DC-link build-up (Fig. 6). Three film capacitors were used as DC-link capacitance at all set-ups. Furthermore, another LinkPack module was additionally equipped with ceramic capacitors (Fig. 5) to reduce power loop inductance to 1.6 nH. The switching behaviours of all three modules were recorded. The comparison was performed with 600 V DC-link voltage and 200 A load current. The overall gate resistance was 5.5 Ω at each build-up.
Turn-on and turn-off switching transitions are shown in Fig. 8. Turn-on behaviour of both new modules is slightly smoother than the reference which clearly shows oscillations at low side voltage and DC-link voltage. The turn-on transition time is 466 ns in all three cases.
Turn-off durations of 95 ns of both LinkPack modules are clearly lower than a duration of 108 ns of the reference module. The switching over-voltage of 121 V of the new module with film capacitors only is slightly higher than the over-voltage of 108 V of the reference module which is not the expected result. Due to significantly lower power loop stray inductance the over-voltage was expected to decrease, as several promising publications show [2, 9, 10], although the dV/dt gradient is 27% stepper. However the comparison is not fully qualified as the Si free-wheeling diodes in the new inverter module are inflated by factor two compared to the reference module to reduce the transmitting losses as operation is mainly in free-wheeling mode. However, the turn-off over-voltage of 79 V of the LinkPack module with additional ceramic capacitors is 29 V smaller compared to the reference module's value. Nonetheless, the performance of modern acquirable Si power modules with appropriate optimised low inductive DC-link build-up is hard to beat by using new Si module designs as they provide very good switching behaviour.

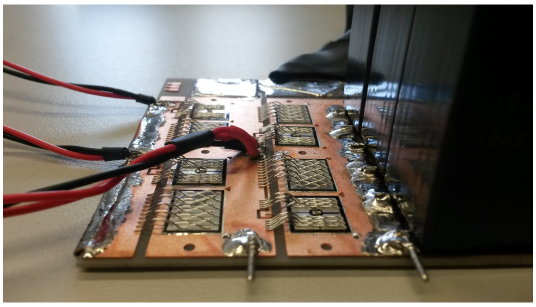

Figure 4: Soldered and bonded Si-IGBTs and Si-diodes at LinkPack module.

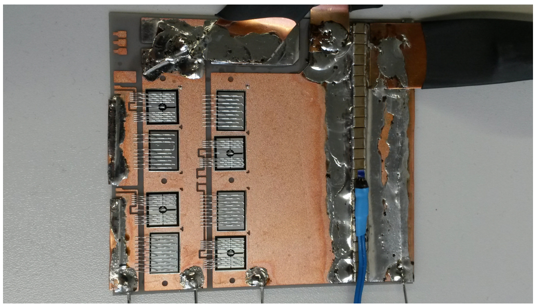

Figure 5: Additional ceramic capacitors soldered onto the AlN DCB (film capacitors are removed).

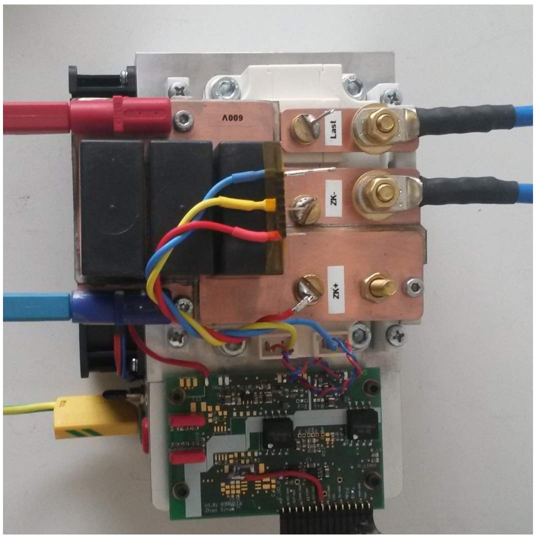

Figure 6: Reference module.

Figure 7: Low inductive Si LinkPack module.

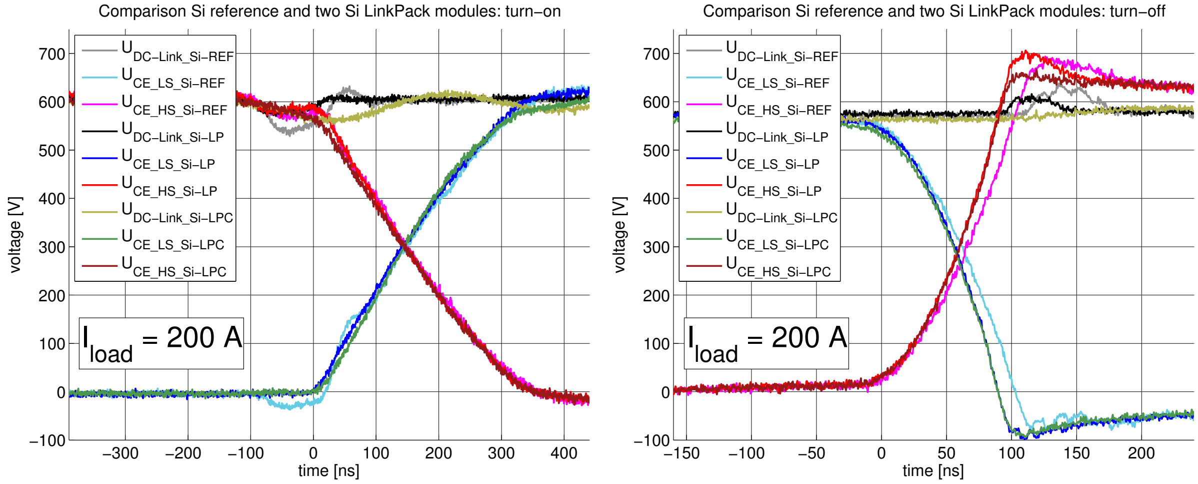

Figure 8: Comparison of switching behaviour of Si-IGBTs / Si-diodes LinkPack module with film capacitors only (Si-LP), Si LinkPack module with film and additional ceramic capacitors (Si-LPC) and Si reference module from SEMIKRON [8] (Si-REF). Left: turn-on process, right: turn-off process.

4.2 Hybrid modules

Switching behaviours of hybrid modules are depicted in Fig. 9. Instead of Si-diodes, hybrid modules are equipped with SiC-diodes. The Si-IGBT semiconductors stay unchanged. The hybrid LinkPack modules were compared to a hybrid reference module SKM200GB12T4SiC2 from SEMIKRON [11]. Again, the comparison was performed with 600 V DC-link voltage, 200 A load current and an overall gate resistance of 5.5 Ω at each build-up.

Turn-on transitions of the LinkPack module with film capacitors only and the LinkPack module with film and additional ceramic capacitors are significantly smoother than the turn-on event of the hybrid reference module. Last-mentioned shows distinct oscillations of up to 130 V peak at low side and DC-link voltage and slight oscillations at high side voltage. Turn-on durations of all three modules are 367 ns. Turn-off behaviour reveals a significantly accelerated switching transition of the new LinkPack modules. The turn-off duration decreases from 124 ns at reference to 100 ns at LinkPack modules. Furthermore, the turn-off over-voltage clearly decreases from 107 V (reference) to 93 V (LinkPack with film capacitors only) respectively 64 V (Linkpack with film and ceramic capacitors). Therefore, the new LinkPack design significantly improves switching behaviour of Si-IGBTs / SiC-diodes modules concerning oscillations, speed and over-voltage compared to conventional hybrid modules.

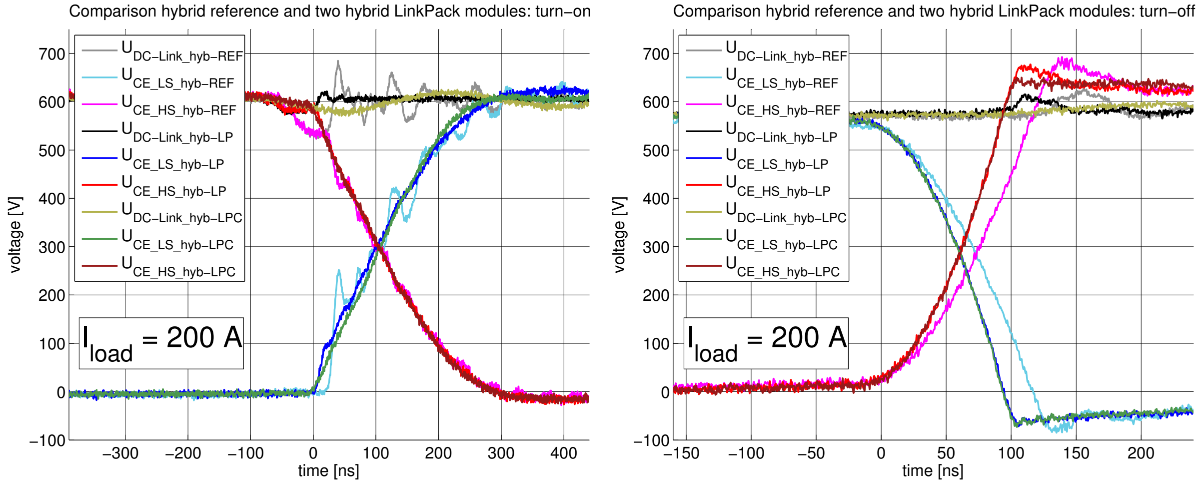

Figure 9: Comparison of switching behaviour of Si-IGBTs / SiC-diodes LinkPack hybrid module with film capacitors only (hyb-LP), LinkPack hybrid module with film and additional ceramic capacitors (hyb-LPC) and hybrid reference module from SEMIKRON [11] (hyb-REF). Left: turn-on process, right: turn-off process.

4.3 Full SiC modules

Fig. 10 shows SiC-Mosfet bare dies soldered and bonded onto a LinkPack AlN DCB and a finalised SiC LinkPack module with film capacitors only. The comparison of switching behaviour of LinkPack modules equipped with SiC-Mosfets and full SiC reference CAS300M12BM2 from Wolfspeed [12] provides measurement graphs depicted in Fig. 11. As during previous measurements, the comparison was done at 600 V, 200 A and with 5.5 Ω overall gate resistance. The novel LinkPack design enables a considerable faster turn-on transition compared to the SiC reference's value of 153 ns. LinkPack with film capacitors only achieves a value of 115 ns. LinkPack module with additional ceramic capacitors undercuts this time to significant small 93 ns. Furthermore, voltage oscillations at low side and DC-link voltage of reference module are very distinct, whereas oscillations of LinkPack module with film capacitors only are much smoother. Voltage curves of LinkPack module with both, film and ceramic capacitors, reveal hardly any noticeable oscillations.
Turn-off speed of the new full SiC modules distinctly increases compared to the SiC reference. Turn-off transition time decreases by 21 ns from 82 ns of reference module to 61 ns of both SiC LinkPack modules. Switching over-voltage of SiC reference amounts 167 V. The new module design with film capacitors only reduces this value to 113 V. The addition of ceramic capacitors further significantly lowers this value by 91 V down to 76 V compared to SiC reference module's turn-off over-voltage. Reducing typical voltage ringing at the application of fast-switching SiC semiconductors is a big challenge and a main topic in various publications [13, 14]. LinkPack modules show a very smooth switching behaviour revealing almost no ringing compared to switching behaviour of other SiC power modules [15, 16].

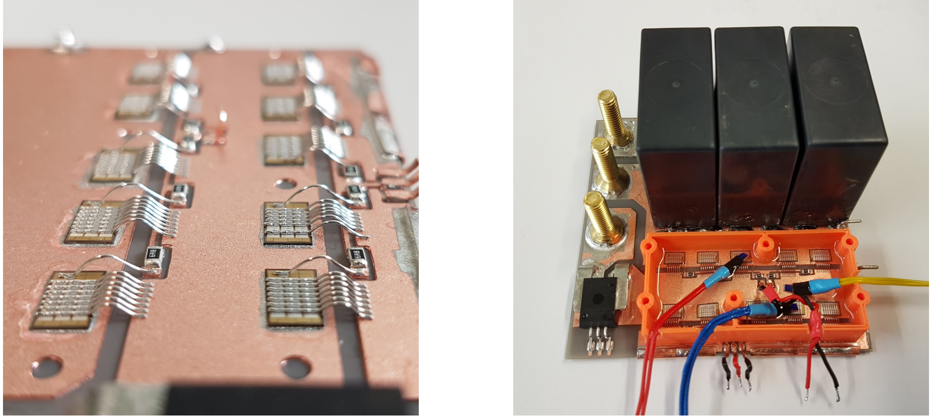

Figure 10: Left: Soldered and bonded SiC-Mosfets at LinkPack module. Right: SiC-Mosfets LinkPack module with film capacitors only.

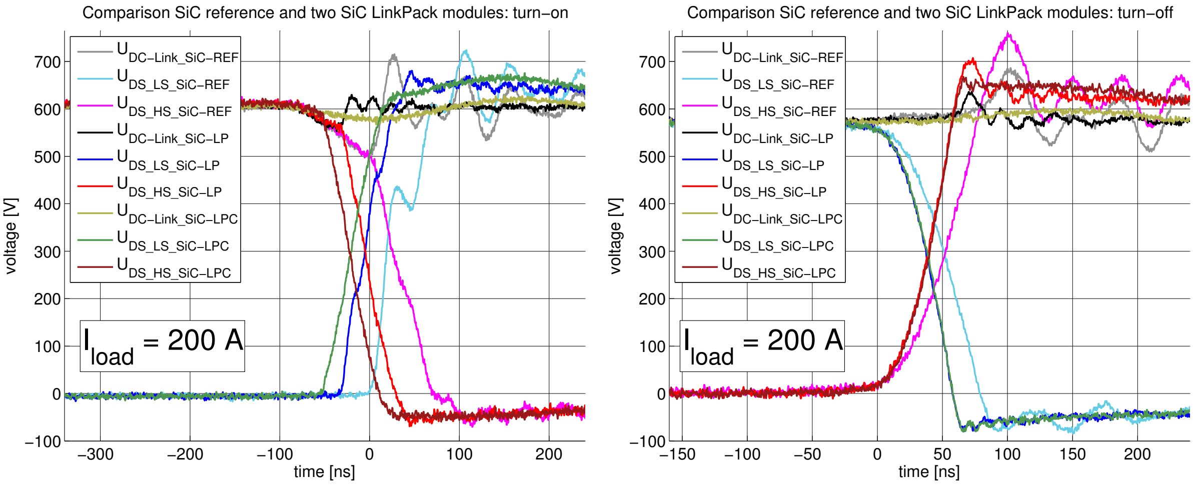

Figure 11: Comparison of switching behaviour of SiC-Mosfets LinkPack module with film capacitors only (SiC-LP), SiC-Mosfets LinkPack module with film and additional ceramic capacitors (SiC-LPC) and full SiC reference module from Wolfspeed [12] (SiC-REF). Left: turn-on process, right: turn-off process. The x-axis of turn-on process is spread compared to Si and hybrid plots.

5 Conclusion

The paper presents a 600 V / 200 A power module with integrated common mode EMI shielding. Using a novel design, an ultra-low stray inductance value of 1.35 nH plus the mounted capacitor's ESL can be achieved. The film capacitor's contribution of stray inductance (ESL) significantly increases the overall commutation loop's inductance to 7.65 nH. To reduce this value to 1.6 nH, optional additional ceramic capacitors are mounted underneath the film capacitors. The necessary additional insulation layer increases the thermal resistance of the cooling path of the new module. However, this effect is compensated by a significantly better switching performance allowing reduced switching losses and an effective common mode EMI shielding [5].

Turn-on switching speed of Si and hybrid LinkPack modules remains at the same value as of conventional modules. However, distinct voltage oscillations at DC-link and low side voltage can be significantly reduced, which is a improvement concerning EMC. Turn-on speeds of full SiC modules can be increased by up to 65% compared to conventional SiC modules using LinkPack design with additional mounted ceramic capacitors. Furthermore, the turn-off speeds of the new modules can be significantly increased by up to 34% compared to references. Simultaneously, a noticeable reduction of switching over-voltage of up to 91 V is achieved, allowing a reduced safety margin from applied DC-link voltage to maximum drain-source breakdown voltage of used semiconductors.

6 Further steps

Next steps will focus on determining the switching and conducting losses of the LinkPack and reference modules presented in this paper. Furthermore, the novel LinkPack design will be modified applying a ceramic material instead of the current electrical insulation film layer to improve cooling performance. Further improvements of switching behaviour and losses are planed involving the use of copper thick film technology to continue reducing the module stray inductance.

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Thomas Huber studied Electrical Engineering at the University of Applied Sciences Landshut, Germany. In 2015 he received the M.Eng title. The topic of his master thesis was the development of a traction inverter for an electrical formula student race car. His thesis was awarded with the Bavarian culture award. Since that time he is doing a cooperative doctorate at UAS Landshut in the group of Prof. Dr. Kleimaier and at TU München at the institute of Prof. Dr. Kennel. Mr. Huber does research on new low-inductive power module designs.

Alexander Kleimaier studied Electrical Engineering at the Karlsruhe Institute of Technology from 1992 to 1998. In 2003 he finished his PhD studies at the Technical University of Munich. After his doctorate, he joined Compact Dynamcis GmbH in Starnberg, Germany. In 2007, he became Head of Development Electronics and was responsible for power electronics and the control of novel electric motors and actuators. Since 2011 he is Professor at the University of Applied Sciences in Landshut, Germany. His fields of research are control of electrical drives, new variants of PMSMs and inverters with ultra low inductive design.