SiC Boost Converter with 3D-Printed Fluid Coolers and Inductor Bobbins

A highly integrated two-phase interleaved bidirectional boost converter using discrete SiC MOSFETs and 3D-printed fluid coolers as well as 3D-printed inductor bobbins was awarded as the Best Paper of PCIM 2018. The converter is operated at a high switching frequency of 400 kHz and features a very high power density of 42.1 kW/dm^3 (or 26.9 kW/kg respectively) including control hardware while delivering 19.8 kW of output power. This subject was awarded as PCIM Europe 2018 Best Paper co-sponsored by Power Electronics Europe. **Arne Hendrik Wienhausen, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Aachen, Germany**

Commercially available SiC power modules such as Wolfspeed CCS050M12CM2 feature a high parasitic inductance of approx. 30 nH in the power path with all three available phases in parallel, which limits the achievable switching frequency. Discrete SiC MOSFETs with kelvin source connection offer a better switching performance. Therefore, the switching frequency can be raised, smaller passive components can be used and system costs can be reduced. Thus Wolfspeed C3M0065100K SiC MOSFETs in TO-247-4 packages are used which are operated at switching frequency of 400 kHz. The converter is designed to boost an input voltage of 400 V to an output voltage of 800 V or vice versa. Converters in this voltage range are used e.g. in automotive applications to enable a variable DC link voltage.

In order to further reduce the converter size, 3D-printed fluid coolers are used. With these miniature fluid coolers a high power density can be realized. The 3D-printed water coolers were developed and manufactured by IQEvolution according to the specifications resulting from the dimensioning of the converter.

With high switching frequencies, carefully designed magnetic components are required. Therefore, water cooled inductors which are optimized for high-frequency operation were developed.

Converter electronics

The electronics located on three stacked PCBs occupy only 0.19 dm^3 of space (box around the converter). This includes all power semiconductors, gate drivers and associated isolated supply, input and output capacitors, the 3D-printed fluid cooler and all electronics necessary for the control of the converter (Figure 1). Besides an FPGA and an MCU, galvanically isolated current measurement circuits for each phase and isolated voltage measurement circuits for the input and output voltages are integrated.

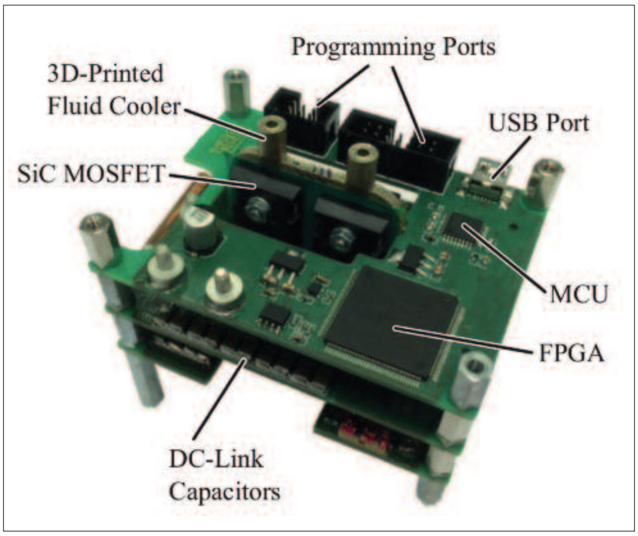


Figure 1: Converter electronics without inductors

As depicted in Figure 2, the water-cooled boost inductors are located below the electronics. The inductors are potted together with a 3D-printed fluid cooler to dissipate copper and core losses. The potted boost inductors feature a total volume of 0.28 dm^3, which leads to overall converter volume of 0.47 dm^3. In total, the converter features a weight of only 735 g while the potting compound highly contributes to the converter weight. This results in a weight-specific power density of 26.9 kW/kg. This value includes all control hardware and the dual inductor.

The converter electronics are optimized for high-frequency operation and a small total volume. The used SiC MOSFETs can be operated safely with a unipolar gate voltage of 15 V, which significantly reduces the complexity of the gate driver supply and the required board space. The low total gate charge Q_g of 35 nC, combined with the low driving voltage V_g, results in a very low gate power of only 210 mW per transistor at a switching frequency fs of 400 kHz.

As gate driver, 1EDI60N12AF from Infineon is used, which is specified for high switching frequencies of up to 4 MHz and high common-mode transients of 100 kV/µs. The integrated galvanic isolation of the gate driver keeps the required board area small. The drivers are supplied by one DC/DC converter each (Murata NXE2). These small surface mounted converters feature a coupling capacitance of only 2.1 pF, which is of utmost importance when high common-mode transients are applied. The common-mode current through the isolation barrier is directly proportional to the voltage slope and the parasitic coupling capacitance. Therefore, the coupling capacity has to be kept small in the presence of high common-mode transisients.

The gate drivers and the DC/DC

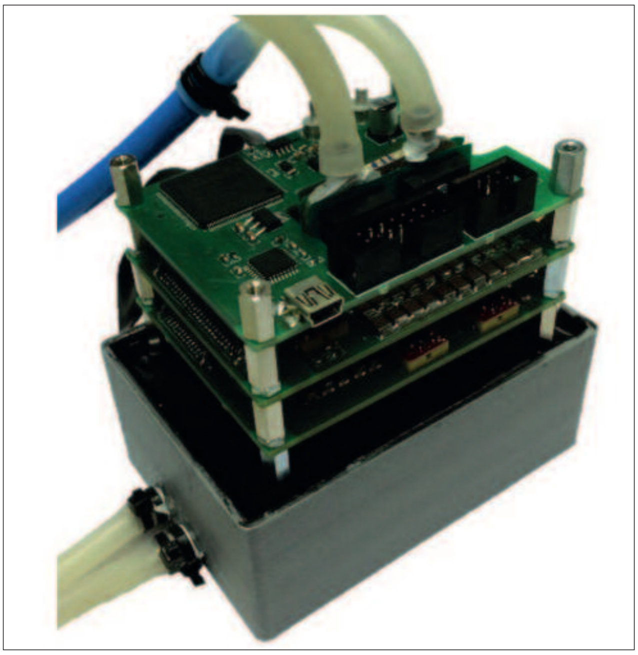


Figure 2: Converter including potted inductors

converters are mounted directly above one another on opposing board sides. This keeps the kelvin source referenced copper islands, which are directly connected to the switching node, very small (less than 1 cm^2) and, therefore, minimizes their parasitic capacitance. The contribution of the PCB cannot be neglegted as only 1 cm^2 of copper with a distance of 300 µm in FR4 results in a capacitance of 12.4 pF, which is nearly six times the coupling capacitance of the used DC/DC converters.

Galvanically isolated current sensors with a band-width of 1 MHz and a small footprint (SO-8) are used for each phase of the converter (AllegroACS730). The acquired signals are fed through fully-differential filter stages into a high-speed ADC, which features a differential input and LVDS outputs for a high signal integrity (Linear Technology LTC2311-12). High-precisionoptocouplers (Broadcom ACPL-C87A) are used to isolate the input and output voltage measurement circuit from the control logic.

As input and output capacitance, 184 ceramic SMD capacitors in 1812 package are used which are distributed over the PCB and interconnected by four to six interleaved power planes for a minumum DC link inductance. This leads to a total input capacitance of 16.2 µF and a total output capacitance of 7.6 µF.

A low-cost Spartan 6 FPGA is used for control purposes. It reads out the ADCs for current and voltage measurements and generates the gate signals for the power transistors. A low-cost Cortex-M0+ MCU is used as a USB-to-SPI bridge for communication with a PC. As the control logic is isolated from the power electronics, the communication can be realized without any isolation.

To obtain a high PWM resolution, four high-speed clocks are used within the FPGA each of which is phase-shifted by 90°. These clocks are fed into an asynchronous output logic which generates the required PWM pulses with a resolution four times higher than achievable by a single clock of the same frequency. In the presented converter design, a PWM resolution of 1.25 ns is realized.

3D printed fluid coolers

The 3D-printed fluid coolers are designed to achieve space efficient cooling of four power transistors in a TO-247 or TO-220 package. Due to 3D-printing, the shape of the fluid cooler can be adopted to fit nearly any other transistor package or other geometric constraints. A clear view on the 3D-printed fluid cooler with mounted SiC MOSFETs is shown in Figure 3.

The fluid coolers are produced from nickel which represents a good compromise between mechanical robustness and thermal conductivity. In order to compare different materials for the miniature fluid cooler, also a stain-less steel and a copper version of the cooler were produced and characterized. While the first nickel prototype still has a weight of 20.2 g, which corresponds to 2.7 % of the total converter weight including inductors, the even smaller version weights only 16.6 g. Both cooler sizes are designed to dissipate 400 W of losses. The reduced weight and height of the smaller version results in a significantly shorter production time and, due to the SLM (Selective Laser Melting) process, production time contributes most to the cooler costs.

Fluid cooled inductors

A water cooled set of boost inductors was developed, featuring various advantages compared to classic (litz) wire wound approaches. The inductors share a common 3D-printed plastic bobbin which serves as place holder and isolation for the used copper foil.

The inductors are potted together with a 3D-printed fluid cooler for efficient cooling within minimum space. For an optimal result, potting is done in a vacuum chamber to extract all enclosed air from the potting compound. The internal structure of the dual inductor is depicted in Figure 4. The copper foil is placed inside the spiral slot of the 3D-printed plastic bobbin before the 3D-printed top plate is fitted to serve as an isolation to the top ferrite core half.

Both inductors share one common 3D-printed fluid cooler. In order to reduce eddy currents in the metallic cooler induced by the winding parts which are not surrounded by ferrite material, the cooler is dimensioned slightly smaller than the ferrite cores. cooled inductors. A plastic spacer is fitted between the metallic 3D-printed water cooler and the inductors in order to further minimize eddy currents. This spacer also serves as a separator between the two ferrite cores. Tolerances during production can be kept extremely small with the use of modern high precision 3D printers (Figure 5). As a consequence, the two integrated inductors feature nearly identical characteristics, which is beneficial in terms of current distribution

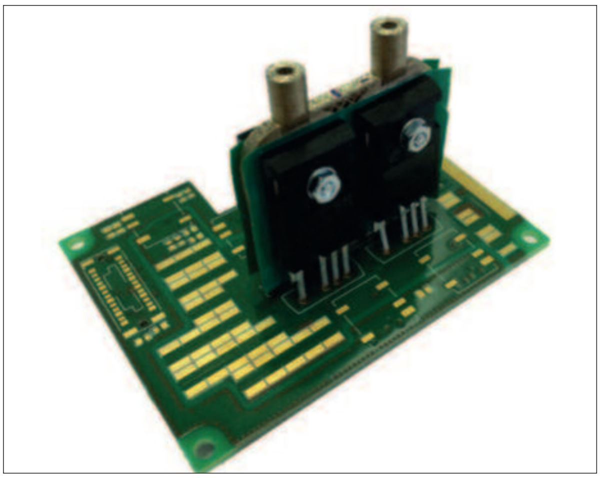
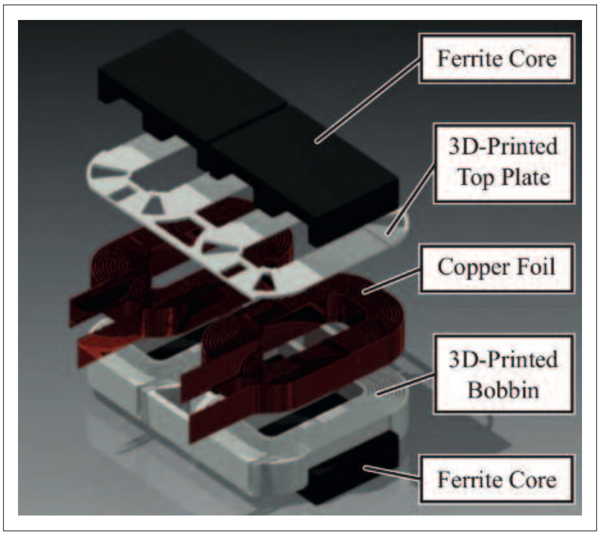
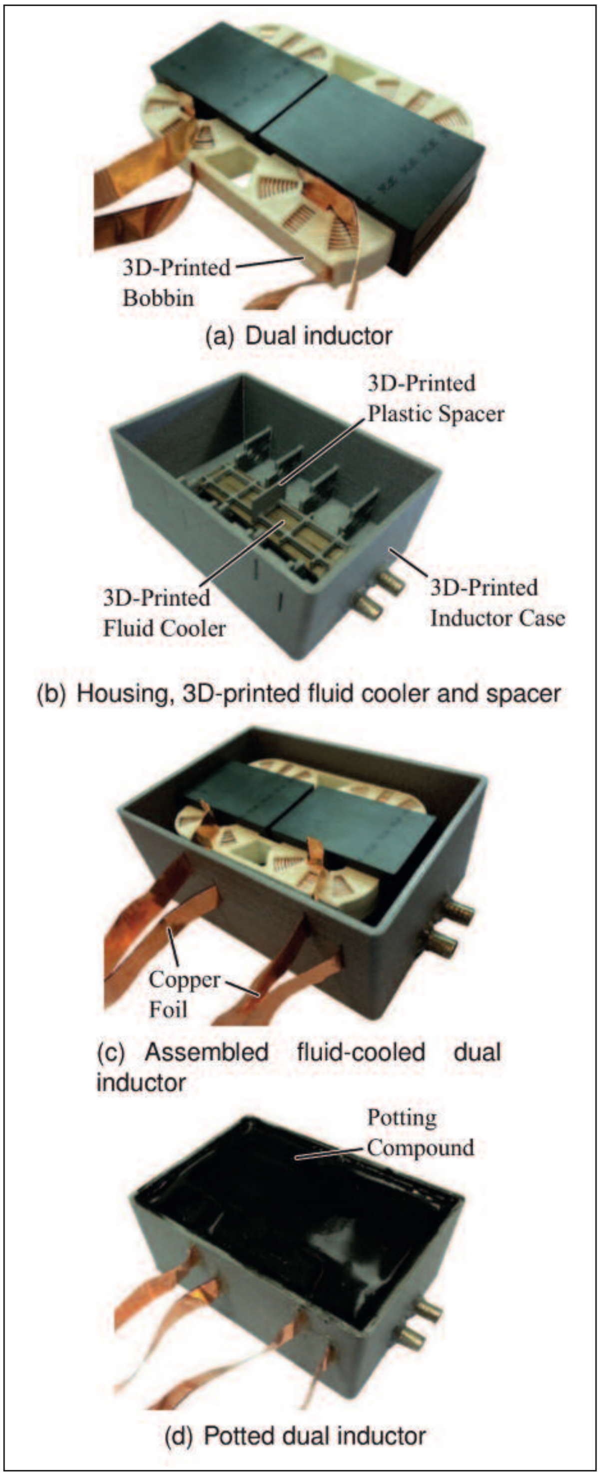


Figure 3: 3D-printed water cooler with mounted SiC power transistors



ABOVE: Figure 4: **Internal structure of the liquid cooled dual inductor**



RIGHT: Figure 5: **Production steps for the fluid-cooled dual boost inductor**

between the phases of a multi-phase converter.

Experimental results

In order to characterize the 3D-printed fluid coolers produced from different materials, four MOSFETs are mounted on each version. An electrically isolated thermal interface material (TIM) is used to prevent short circuits between the transistors. K-Type thermocouples are used to measure the fluid temperatures in the inlet and in the outlet of the cooler as well as the cooler temperature. The internal body diodes of the transistors are used to generate controllable losses.

Efficiency measurements have been conducted at a high switching frequency of 400 kHz and input voltages of 200 V and 400 V. The duty cycle was kept constant at 50 %. During the first measurements, the power was limited to 15 kW by the used power source. Efficiency measurements for higher output powers were conducted in a back-to-back configuration. The auxiliary converter is operated as a controllable current sink and feeds energy back to the 400 V input DC rail. In this configuration only system losses of the two converters have to be covered by the power source. At output power of 19.8 kW, a total loss of approx. 600 W can be dissipated effectively with the two 3D-printed fluid coolers.

Conclusion and outlook

A highly compact and light-weight 19.8 kW bidirectional boost converter operated at a very high switching frequency of 400 kHz using discrete SiC MOSFETs has been presented. With a total converter volume of 0.47 dm^3 and a total converter weight of 735 g, it features a very high power density of 42.1 kW/dm^3 and 26.9 kW/kg. This is enabled by the use of 3D-printed water coolers for the power transistors, as well as for the potted inductors. These inductors are developed and optimized for high-frequency operation and show excellent reproducibility due to the use of 3D-printed bobbins equipped with copper foil which is very beneficial in a multi-phase converter.

Measurement results show high efficiencies over a wide load range even though the converter is operated at a very high switching frequency. 3D-printed fluid coolers allow space efficient cooling of power electronic components and can be shaped to fulfill nearly any geometric constraint. Highly compact power converters with very high power densities can be realized by the use of miniature fluid coolers. The converter size can be reduced further more by the use of a shared 3D-printed fluid cooler for the power transistors and the power inductors as well. Also, the volume filled with potting compound can be decreased, which significantly reduces the weight. The thermal performance of the transistor cooler can be enhanced further more by a ceramic coating on the surface of the 3D-printed fluid cooler, which allows the use of a TIM.

Literature

"Highly Integrated Two-Phase SiC Boost Converter with 3D Printed Fluid Coolers and 3D Printed Inductor Bobbins", PCIM Europe 2018 Proceedings, pages 317 - 324