A SiC-Based 100 kW High-Power-Density (34 kW/L) Electric Vehicle Traction Inverter

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***Abstract*— A SiC-based high power density (34 kW/L) Electric vehicle (EV) traction inverter is developed for 105℃ ambient temperature operation and 100 kW peak power output. The thermal properties of this high-temperature system are analyzed and the system is designed based on the thermal behavior of the switching devices. The liquid cooling system is designed and testing approach is proposed to estimate the maximum device die temperature. The key components, such as dc-link capacitors and dc busbar are designed and arranged to achieve high power density at high ambient temperature. The system prototype has been built and tested up to 60 kW continuous and 100 kW for 20 seconds, at 105°C ambient temperature and 65°C coolant temperature.**

Keywords*— *SiC, Electric vehicle (EV), traction inverter, high power density

I. Introduction

Modern electric vehicles require high-power-density traction inverters to operate reliably at high ambient temperatures. In Hybrid Electric Vehicles (HEVs), these converters usually require dedicated liquid cooling system to provide sufficient cooling capability and dissipate the heat from the power semiconductor switches. These dedicated cooling systems operate with coolant temperatures typically around 65°C or less, which is much lower than the temperature of the coolant in the engine cooling system [1]. Using Wide Bandgap (WBG) semiconductor devices in traction inverters makes it possible to have only one high-temperature cooling loop in HEVs because higher junction temperature of WBG devices enables them to operate with higher coolant temperature. On the other hand, some air-cooled converters are placed away from electrical machine to obtain desired low ambient temperature, which could cause electromagnetic interference (EMI) issues as well as space arrangement problems [2]. With higher junction temperature WBG devices, these converters can be more compact and placed in the engine compartment when other components are appropriately designed for high ambient temperate operations. Therefore, high-power-density high-ambient-temperature inverters are requested in Hybrid EVs as well as in other application areas, like the aerospace industry [3].

In [4], the design of a 120°C ambient temperature forced air-cooled automotive inverter by using SiC JFETs is proposed. An accurate thermal model and an optimized active cooling by using a Peltier cooler are analyzed. Although the proposed air-cooled system can help inverter operate at very high ambient temperature, the power density is sacrificed due to the bulky heatsink compared to liquid-cooled system. In addition, liquid-cooled system can provide much smaller thermal resistance, which can dissipate more heat from the switching device, thus can potentially help inverter deliver more power to the electrical machine than the air-cooled system.

A 30 kVA SiC MOSFET inverter is designed and evaluated for 180°C ambient temperature operations in [5]. However, the switching devices require complicated cooling system design to dissipate the heat to the coolant, thus high-power-density was not the priority in this design. Additionally, not all the components were designed to operate at high temperature, which is required when both active and passive devices in automotive converters operate in high-temperature ambient.

A SiC-based high-power-density EV traction inverter developed for 105°C ambient temperature operation is presented in this paper. The developed inverter is capable of 100 kW peak power at 65°C coolant temperature. The key parameters are shown in the Table I. In Section II, thermal operating points for SiC devices are analyzed based on the thermal behavior of the switching devices. Liquid ccooling system design based on the inverter thermal model is presented in Section III. The selection of other key components and their

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TABLE I. KEY PARAMETERS OF 100KW INVERTER

Parameters	Value
Input DC Voltage	400 V
Output Power	100 kW
Switching frequency	40 kHz
Power Density	>30 kW/L
Ambient Operation Temperature	-40 to 105°C

arrangement aiming to achieve high power density are discussed in Section IV. The theoretical findings are verified by the experimental data obtained from a laboratory prototype, as presented in Section V, and Section VI concludes the paper.

II. The Thermal Operating Point Considerations

In the design process of a power electronic converter, the junction temperature should never exceed the preset limit under any circumstances. In other words, the thermal operating point of the system should be designed to be in a safe and optimum range, which is determined by the power losses in the switching devices and the properties of the cooling system. The inverter power loss P_{loss} is defined as a function of junction temperature T_j, output power P_{out} and switching frequency f_{sw}, while cooling power P_{cool} is defined as a function of junction temperature, input coolant temperature $T_{coolant}$ (ambient temperature for air-cooled system) and total thermal resistance $R_{th,total}$, (1). These two powers are the same in the steady state and the junction temperature can be determined from (2) when the coolant temperature and the total thermal resistance are given.

$$P_{cool} = (T_j - T_{Coolant}) / R_{th,total} \tag{1}$$

$$P_{cool}\left(T_j, T_{coolant}, R_{th,totoal}\right) = P_{loss}\left(T_j, P_{out}, f_{sw}\right) \tag{2}$$

To study the power losses P_{loss}, a 100 kW three-phase inverter model is built in PLECS, in which MOSFET and Diode PLECS models are provided by the manufacturer. The module typical performance including switching losses and conduction losses can also be obtained from double-pulse tests. Simulations have been done at output power ranging from 30 kW to 100 kW, and junction temperature ranging from 25°C to 175°C, with fixed switching frequency of 40 kHz. The results are imported into MATLAB, and presented as a power loss surface (as shown in Fig. 1) by applying MATLAB's polynomial curve fitting tool. The cooling system performance can be illustrated in the same coordinate system by a flat surface, as illustrated in Fig. 2. The two flat surfaces in Fig. 2 correspond to two different total thermal resistances at the same coolant temperature. The intersection of cooling power and loss power defines the possible thermal operating points. The intersection shows that the better cooling system corresponds to lower junction temperature at same output power, or more output power at same junction temperature. If the coolant temperature is fixed to 65°C, the 3D plot reduces to a 2D plot, as shown in Fig. 3.

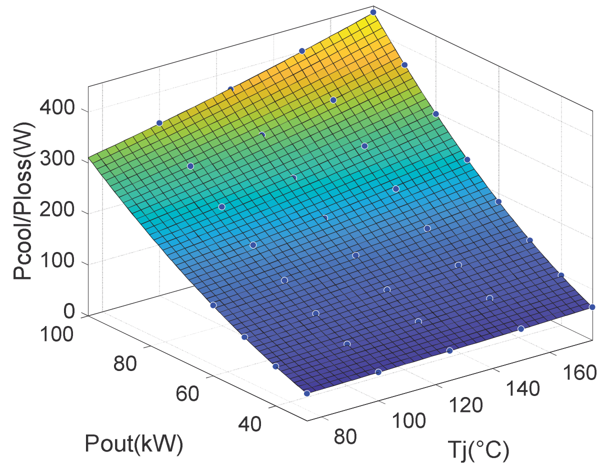

Fig. 1. The inverter power loss surface.

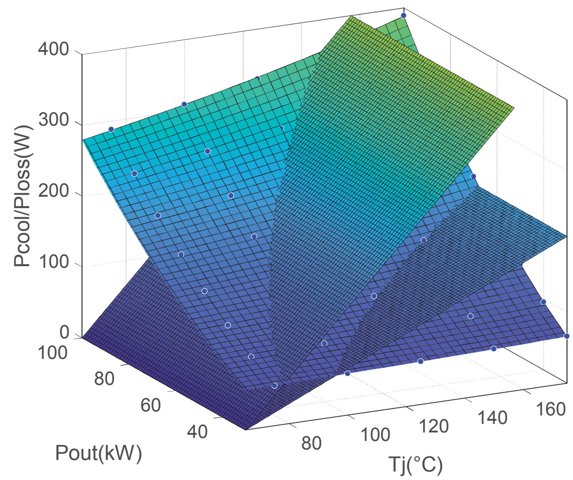

Fig. 2. The possible thermal operating points are defined by the intersection of the power loss surface and the cooling loss surface.

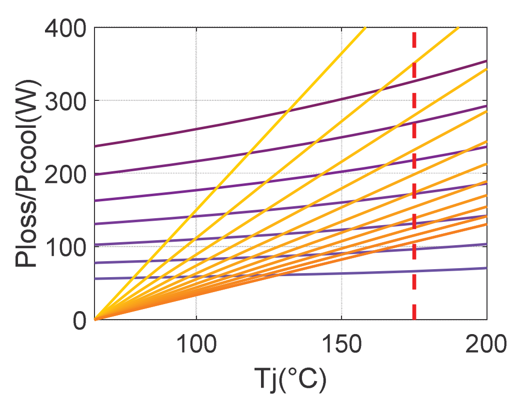

Fig. 3. The possible thermal operating points in 2D plot. The orange lines represent different cooling system and the violet lines are the power losses for different output power levels. The red line is the junction temperature limitation.

The orange lines represent different cooling system and the violet lines are the power losses for different output power levels. The points on the left side of the red line are the safe operating points (less than 175°C junction temperature). To keep the junction temperature below 150°C (having 25°C margin), the maximum allowable total thermal resistance from junction to coolant is determined to be 0.23 °C/W based on the proposed thermal model, which will result in 2150W total losses at 100kW.

III. Thermal Modeling and Cooling System Design

The thermal model of the inverter is illustrated in Fig. 4. The total thermal resistance is the sum of MOSFETs junction-to-case thermal resistance $R_{th,jc}$, thermal interface material (TIM) thermal resistance $R_{th,TIM}$ and cold plate thermal resistance $R_{th,cp}$ (3). Since the junction-to-case resistance is given by the module package, it is important to carefully test and select the optimal TIM and the cool plate.

The TIM is tested and selected based on the following procedure. First, the $R_{ds,on}$ of a specified module (CAS325M12HM2 from CREE) is measured at different temperatures (ranging from 25°C to 150°C) to obtain the relationship between the conduction resistance and junction temperature, as illustrated in Fig. 5 (grey curve). The measured resistance is about 0.3 mΩ higher than the curve from the module datasheet (red curve), which is mainly because the measured resistance includes connection resistance on the module level, whereas the datasheet provides only the resistance on the chip (die) level. Second, the characterized module is placed on a selected cold plate and conducts 300 A DC current to generate substantial conduction loss. The drain-source voltage is then measured in the steady state condition (after reaching thermal equilibrium). Finally, the total thermal resistance can be evaluated using (4), where I_D represents the drain-source current (300 A), P_{loss} is the total conduction loss and the junction temperature T_j can be found based on the relationship in Fig. 5. Because the other two thermal resistances are constant, the smaller total thermal resistance is, the better the TIM is. Another way to compare the TIMs is by looking at the drain-source voltage: the lower the drain-source voltage at same drain-source current is, the better the TIM is, which is illustrated in Fig. 6. Two cooling power lines have two intersections with the conduction loss power line, which corresponds to two different operating points. The better cooling system has smaller junction temperature, thus smaller drain-source voltage at same drain-source current.

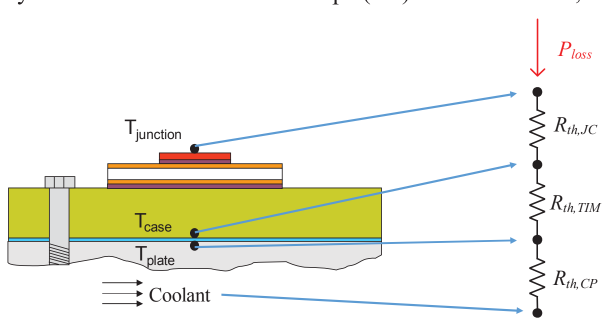

Fig. 4. Inverter thermal model

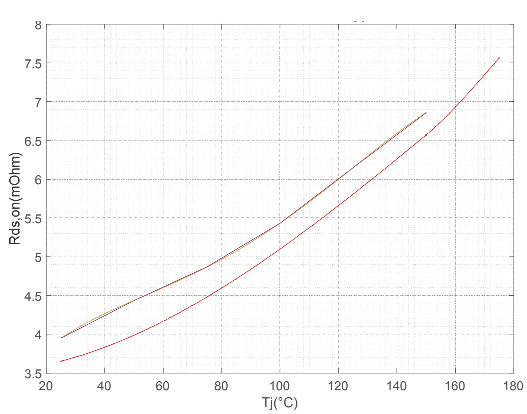

Fig. 5. $R_{ds,on}$ at different junction temperature

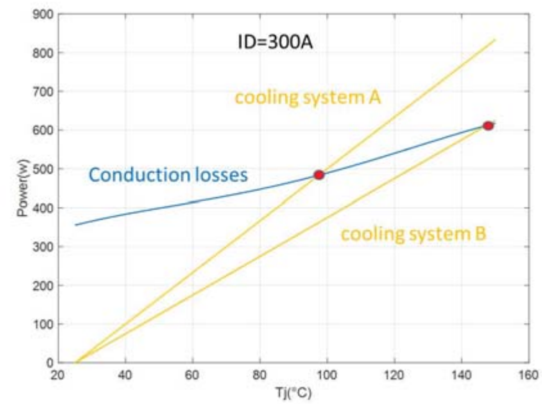

Fig. 6. The illustration of TIM comparison

With standard 62 mm package, modules can be mounted on a commercial 62 mm-wide cold plate. Considering the thermal resistance and pressure drop at 10 L/min, the 007-MXQ-01 cold plate from MaxQ Technology, with a total volume of 0.52 L, is finally selected. The thermal resistance of different cold plates can be compared in a similar way as for the TIMs.

$$R_{th,total} = R_{th,jc} + R_{th,TIM} + R_{th,cp} \tag{3}$$

$$R_{th,i} = \left(T_{j,i} - T_a\right) / P_{loss,i}\,, \qquad P_{loss,i} = V_{ds,i} \cdot I_D = R_{ds,on,i} \cdot I_D^{\,2} \tag{4}$$

IV. Key Component Design and Arrangement

A. DC-link capacitors

The DC-link capacitors are selected based on dc voltage, current ripple, and maximum allowable operating temperature, as well as the required capacitance. Ceramic capacitors usually have high capacitance density and can operate at very wide ambient temperature from -40°C to 150°C. However, they have low capacitance per device, leading to a high number of capacitors required at high power applications. Stacking many capacitors in parallel will increase the system cost and can potentially reduce the reliability due to possible cracks induced by thermal stress. If electrolytic capacitors are selected, the system lifetime could be significantly reduced at elevated temperatures. For example, if TDK's B43693 series capacitors are used, the system lifetime would be reduced from 250,000 hours to 2,500 hours. Although film capacitors also have derating issue at high temperature, they have much longer lifetime, high capacitance per device and lower ESR and ESL. Some manufacturers provide already packaged automotive DC-link capacitors, but they are not flexible for high power density arrangement. Finally, sixteen TDK B32776P film capacitors with a total capacitance of 192 µF, rated dc voltage of 600 V and a ripple current capability of 130 A at 105°C are selected. The total volume of the 16 capacitors is approximately 0.55 L.

B. Busbars

The currents through the AC and DC busbars of a 100 kW three-phase inverter, can be calculated using (5), where PF is the power factor and MI represents the modulation index. Considering the high current-carrying requirements, the required wide operating temperature range from -40 to 105°C, and required good mechanical properties, the copper sheet busbar is preferred over the multilayer PCB approach in this case. Since the high frequency snubber circuit and gate drivers need to be mounted above the modules, the DC-link capacitors are placed beside the module and the cold plate. This arrangement requires two horizontal copper sheets for DC busbar. To further utilize the available space, both DC input power connector and AC output power connector are arranged on the same side of the DC-link capacitors, which finally leads to the design shown in Fig 7. Both the DC and the AC busbar must be machined and bent to the desired shape. The thickness of AC and DC busbar is 4.76 mm and 2.36 mm, respectively, resulting to a total volume of approximately 0.16 L.

$$I_{DC} = P_{in} / V_{DC} ,\quad I_{AC} = P_{out} / (3V_{ph} \cdot PF) = 2P_{out} / (3V_{DC} \cdot PF \cdot MI) \tag{5}$$

C. Other Components

The LEM's HAH3DR-series current sensor (colored white

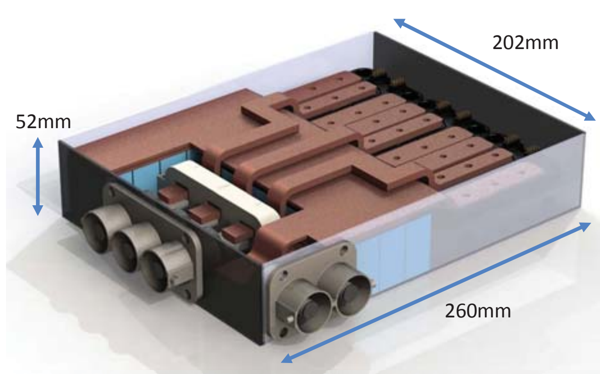

Fig. 7. Inverter design in Solidworks (gate drivers and control board are not shown)

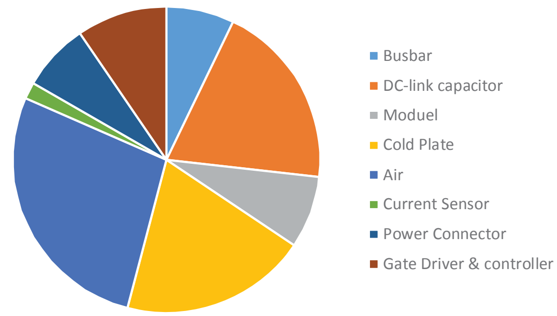

Fig. 8. Inverter volume distribution

in Fig. 7) provides compact way to measure three phase currents up to 900 A in a -40°C to 150°C ambient temperature range. Power connectors from Amphenol Industrial PowerLok Series can carry up to 300 A current with solid mechanical connection to the busbar and the enclosure. The gate drivers and control board are not shown in the picture, but they are placed above the modules and the busbars. The total volume of this design is only 2.9 L (260 mm*202 mm*55 mm), which results in 34 kW/L power density at 100 kW output power. The volume distribution is shown in Fig 8.

V. THE EXPERIMENTAL RESULTS

A 100 kW three-phase inverter prototype is built in Fig. 9 and Fig. 10. The busbar is made in the lab based on the design in Fig. 7. The DC-link capacitors are soldered directly on the busbar and the necessary insulation is achieved by using Kapton tape. The thermal conductive paste WLPK from Fischer Elektronik is selected as the thermal interface material, as discussed in chapter III. The total thermal resistance from the junction to the coolant inlet is only 0.16 °C/W, which meets the requirement. The inverter is assembled and placed in the chamber which controls the ambient temperature. A cooling loop, which is outside of the thermal chamber, provides rated flow rate of the coolant at the rated temperature.

The prototype has been tested at 60 kW for an hour (the inverter reaches thermal equilibrium in 30 minutes) and then at 100 kW for 20 seconds at 105°C ambient. The phase current (green & magenta traces in Fig. 10), the corresponding bottom switch drain-source voltage (light blue) and its gate drive signal (dark blue) are recorded at 100 kW in Fig. 11. Because of the current probe limitation, the phase current is first split by using two conductors in parallel and then measured with two current probes (one of which was measuring the negative value of the current and hence the opposing current waveforms). The phase current is the sum of these two measurements and it was equal to 270A RMS. The measured voltage spikes across the module were acceptable (569.4 V).

To confirm the thermal model described in section 2 and more importantly to make sure all components can safely operate at 105°C ambient temperature, the thermocouples (TC) are implemented in the system. Nine 1 mm deep slots are machined on the cold plate and nine thermocouples are inserted into the slots. The tips of these TCs are placed exactly below the MOSFET dies to measure the hottest points. By applying high thermal conductivity epoxy, the thermocouples can

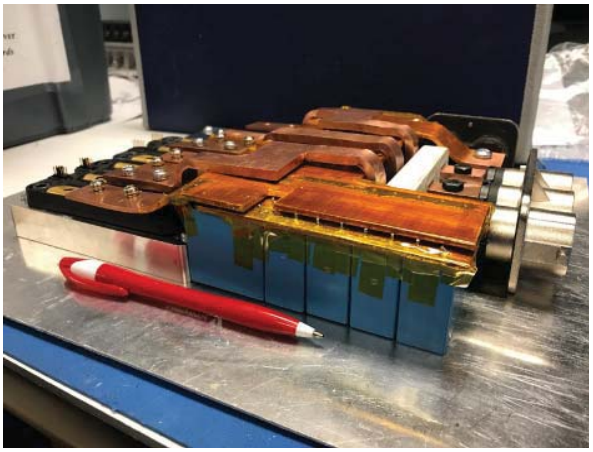

Fig. 9. 100 kW three-phase inverter prototype without gate drivers and controller

Fig. 10. 100 kW three-phase inverter prototype in the chamber

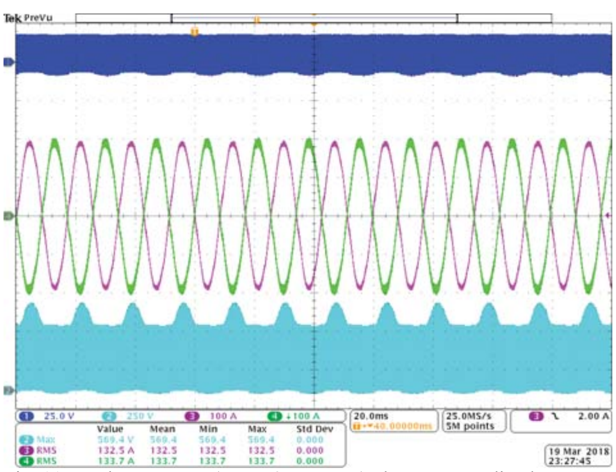

Fig. 11. Phase current (green & magenta), the corresponding bottom switch drain-source voltage (light blue) and its gate drive signal (dark blue) at 100kW

permanently stay in the cold plate, as shown in Fig. 12. Similar process has been done on the baseplates of the modules as well. Thermal measurements are recorded at 100 kW, 105°C ambient temperature and 65°C coolant temperature in Table II.

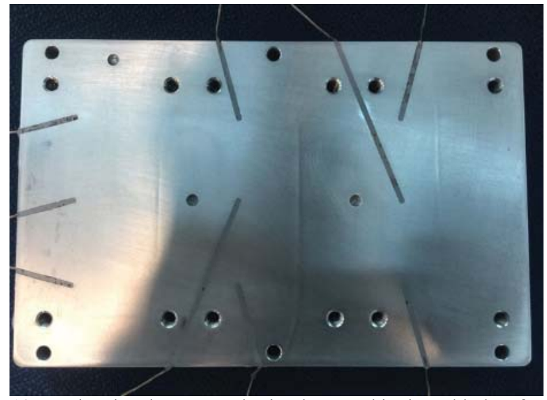

Fig. 12. The nine thermocouples implemented in the cold plate for thermal measurement.

The highest reading of thermocouples in the baseplate is only 93°C and the estimated die temperature is 113°C, which is far below 175°C limitation because the total thermal resistance (0.16 °C/W) is much smaller than the design requirement (0.23 °C/W). Therefore, the inverter output power can increase to more than 100kW potentially.

TABLE II. THERMAL MEASUREMENTS AT 100KW

Position	Temperature
Baseplate	93°C
Cold plate	88 °C
Coolant inlet	65 °C
Coolant outlet	69 °C

VI. CONCLUSIONS

The paper has presented a design of a high-power-density (34 kW/L) SiC-based 100 kW EV traction inverter which operates at 105°C ambient temperature. The MOSFETs thermal operating points are analyzed and designed based on the expected power losses and cooling system ability. Design and testing approach is proposed for liquid cooling system, including the thermal interface material and the cold plate. The inverter prototype is built and tested up to 100 kW at rated ambient temperature. Both electrical and thermal experimental measurements confirm the safe operation of the proposed inverter.

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