Thermal design of stacked power modules for electric drive applications

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***Abstract*—This paper reports the thermal design of a stacked arrangement inserting four IGBT modules between five heat sinks to achieve good cooling performance while enabling them to be installed into the limited space. Such stacked four IGBT modules can be used for a variable voltage converter (VVC), a three-phase motor inverter (M-INV) and a three-phase generator inverter (G-INV) of one electric control system in one electric vehicle or hybrid electric vehicle. Work presented in this paper are the thermally related structure design and thermal-electric and computational fluid dynamics coupled simulation, while the prototyping and thermal test of the stacked arrangement are still ongoing. The simulation results indicate that the stacked arrangement can be designed into a compact 121 mm × 94.7 mm × 90.8 mm structure while achieving the maximum virtual junction temperature below 150 °C under the coolant feed temperature of 70 °C, flow rate of 10 L/min and pressure drop of 0.16 bar for the VVC delivering 150 kW, the M-INV delivering 100 kW and the G-INV delivering 50 kW. If validated with the ongoing work, the stacked arrangement can be employed to increase power density and improve electrical and thermal performance of the power modules in the electric control systems with multiple converters/inverters.**

Keywords—IGBT module, heat sink, double side cooling, stacked structure, simulation, thermal test

I. Introduction

There are generally the power semiconductor modules for three and more converters/inverters which are installed into the limited space in the electric control system of one electric vehicle (EV) or hybrid electric vehicle (HEV) [1,2]. In response to this demand, the stacked arrangements of power modules in which several power semiconductor modules and heat sinks are stacked together were developed [3,4]. However, in the previous stacked arrangements, each of the power modules comprises either single switch or half bridge switch which owns its independent structural, conductive paths and power terminals [1,3-5]. As a result, this may require additional footprint/space to connect the terminals of these modules to the power source, associated connectors, other passive components, and control/drive printed circuit boards (PCBs) for the three and more converters/inverters.

In the present work, a stacked arrangement of Si insulated gate bipolar transistor (IGBT) modules is developed where each IGBT module is integrated with two half bridge switches which share part of conductive tracks of substrates and share part of power terminals. In particular, four such IGBT modules are inserted between five heat sink to form the stacked arrangement with further reduced volume and weight and with better layout of terminals to simplify the associated connections. The four IGBT modules can be used for constructing a variable voltage converter (VVC), a three-phase motor inverter (M-INV) and a three-phase generator inverter (G-INV), and thus increase the power density and improve the electrical and thermal performance of the electric control systems in the electric vehicle (EV) or hybrid electric vehicle (HEV) applications.

The aim of the present thermal design is to ensure the stacked four IGBT modules to achieve good cooling performance while enabling them to be installed into a specified space. The objectives of this paper are to: (i) report the compact structure stacking the modules and heat sinks together; and (ii) optimise the channel design of the heat sinks to meet the cooling requirement under an operating condition for EV and HEV applications. Despite that the stacked arrangement is formed with Si IGBT modules, the methodology and principles developed through the present work can be extended and applied to the development of the stacked arrangement comprising power modules with wide band gaps devices such as SiC and GaN power devices.

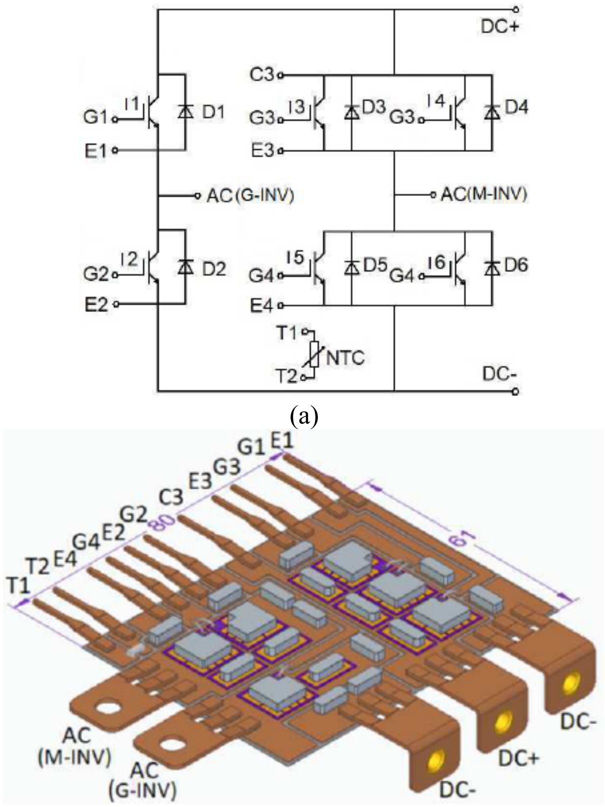
II. Stacked Arrangement

A. Requirement of Structure Design

The design of one electric control system in one EV or HEV requires the IGBT modules and heat sinks which can be installed in a limited space of 125 mm × 100 mm × 96 mm for a VVC, a three-phase M-INV and a three-phase G-INV. The VVC is specified with a maximum output voltage of 500 V and a maximum current of 300A. The M-INV and G-INV are specified both with a maximum direct current (DC) bus voltage of 500 V and respectively with the continuous output currents of 210 Arms and 100 Arms. To meet this requirement, the IGBT modules are designed with the 650V/300A IGBT and fast recovery diode (FRD) chips with the footprints of 12.2 mm × 12.2 mm × 0.07 mm and 12.0 mm × 6.1 mm × 0.07 mm. Each IGBT module is integrated with two half bridge switches which share part of conductive tracks of substrates and part of power terminals. Four such IGBT modules are inserted between five heat sinks to form the stacked arrangement for the VVC, M-INV G-INV.

B. IGBT Module

The IGBT module integrated with two half bridge switches is the same as the one presented in the previous paper [2]. As shown in Fig. 1, one half bridge switch is constructed with two paralleled IGBT chips in antiparallel to two paralleled FRD chips for each switching leg, and the other half bridge is constructed with one single IGBT chip in antiparallel to one single FRD chip for each switching leg. In each IGBT module, all the six IGBT chips, six FRD chips, one negative temperature coefficient (NTC) thermistor and the conductive shim interconnections are enclosed within two ceramic-based substrates to facilitate double side cooling. Both substrates are 0.3/0.32/0.3 mm thick Cu/ceramic/Cu substrates. With moulded epoxy compound encapsulant to provide additional support, the DC+ and DC- terminals are put at one side, the signal/control terminals are put at the opposite side, and the AC terminals are put at a third side of the IGBT module.



(a)

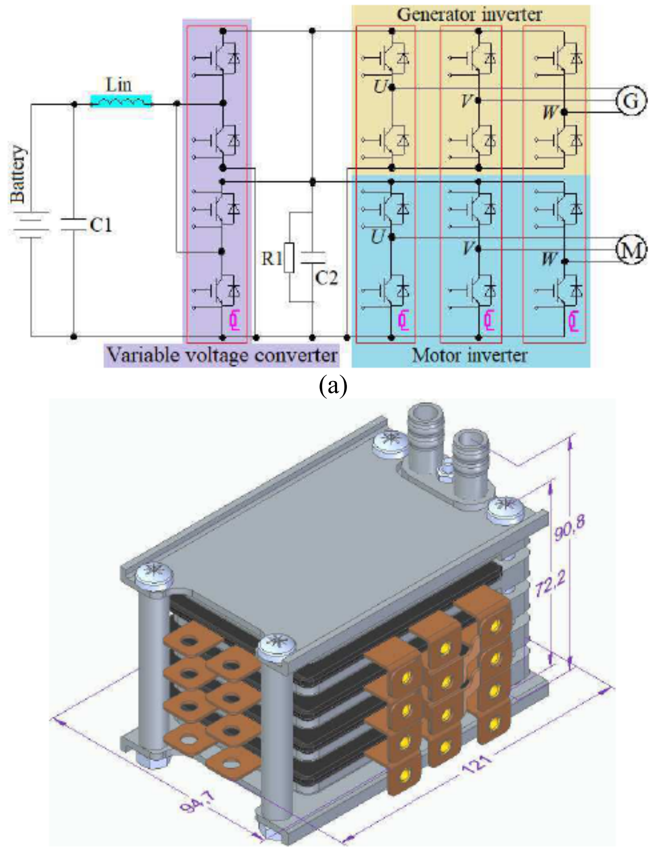
(b)

Fig. 1. The IGBT module integrated with 2 half bridges: (a) topology; (b) the designed structure without the top substrate and moulded encapsulant.

In such an IGBT module, the two half bridge switches share the DC+ and DC- terminals, the conductive track of one substrate directly connected to the collector sides of three IGBT chips and the cathode sides of three FRD chips, and the conductive track of the other substrate connected to the emitter sides of the other three IGBT chips and the anode sides of the other three FRD chips with 2 mm high conductive shims. The conducting paths are designed to achieve low parasitic inductances for the different commutation loops, and slots are added in the conductive tracks of one substrate to balance the parasitic inductances and resistances for the paralleled IGBT and FRD chips [6]. Ignoring the extended terminals, the dimensions of the IGBT module occupied by the substrates and the moulded encapsulant are 89.2 mm × 70 mm × 4.4 mm. The shared terminals and conductive tracks remarkably reduce the footprint and weight of the present IGBT module.

C. Stacked Arrangement

Fig. 2 shows the stacked arrangement inserting four IGBT modules between five heat sinks. The two half bridge switches in the top IGBT module can be connected in parallel to form one half bridge switch. This half bridge switch, and inductor Lin, input capacitor C1, output capacitor C2 and resistor R1 are connected to form the VVC which is employed to step up the voltage of the power source battery. The other three IGBT modules are used as two three-phase half bridge switches. Here each half bridge switch with two paralleled IGBT/FRD chips per switching leg is used as one phase for the M-INV, and each half bridge switch with one single IGBT/FRD chip per switching leg is used as one phase for the G-INV. The shared DC+ and DC- terminals of both three-phase half bridge switches are connected to the output terminals of the VVC. The three AC terminals of the three-phase half bridge switches for the M-INV can be connected to a motor, and the three AC terminals of the three-phase half bridge switches for the G-INV can be connected to a generator.



(a)

(b)

Fig. 2. The stacked arrangement inserting four IGBT modules between five heat sinks: (a) topology of the four IGBT modules in the four red boxes; (b) the designed strucutre.

To form the stacked arrangement, 0.2 mm thick thermal interface materials (TIMs) are placed between each of the four IGBT modules and its two adjacent heat sinks. All the five heat sinks are integrated with cooling channels and two-side cold plates. The inlets and outlets of these five heat sinks are connected in parallel and sealed with O-rings. Two 2.5 mm thick clamping plates attached with 1 mm thick compliant pads are further placed on the top heat sink and under the bottom heat sink. The stacking pressure is applied by bolting the top and bottom clamping plates with 4 pairs of M6 screws and nuts at a specified torque. Including the extended terminals and the extended inlet and outlet connectors of the coolant, the dimensions of the stacked arrangement are 121 mm × 94.7 mm × 90.8 mm. The shared conductive tracks and terminals in each module and the special layout of all the power and signal/control terminals lead to not only reduced volume and weight of the stacked arrangement but also simplified external connections of the four IGBT modules to the inductor, input capacitor, output capacitor, resistor, motor, generator and drive/control PCBs.

III. Thermal Design Consideration

A. *Thermal-Electric Specifications*

Thermal design of the stacked arrangement is to ensure good temperature distribution between the IGBT/FRD chips and the maximum junction temperature below a specified value, i.e. 150 °C, under the worst electro-thermal generation and the specified cooling condition. The latter are estimated following the electrical design and thermal management of the electric control system and the electrical and electro-thermal characteristics of the IGBT and FRD chips. Table I lists the specified parameters of electro-thermal generation and cooling condition for the thermal design of the stacked arrangement inserting the four IGBT modules between the five heat sinks. The coolant flow rate is the total value of the coolant flowing in the five paralleled heat sinks, and the maximum coolant pressure drop is the value across the two top connectors as inlet and outlet of the coolant. Due to the temperature-dependence of the electrical and electro-thermal characteristics of the IGBT and FRD chips, a few iterations between the design of the electric control system and the thermal design of the stacked arrangement should be done for estimating the power losses of the IGBT and FRD chips.

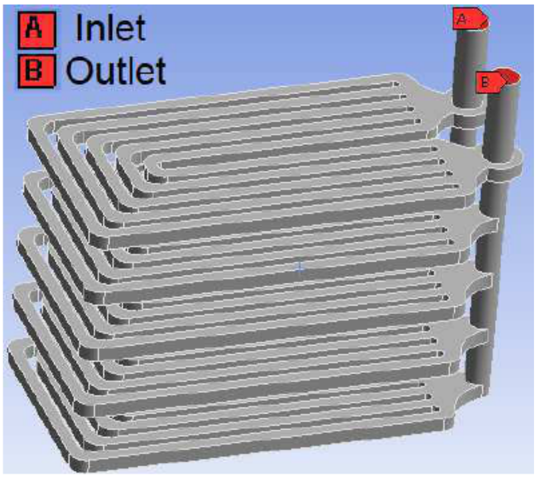
TABLE I. SPECIFICATIONS OF ELECTRO-THERMAL GENERATION AND COOLING CONDITION FOR THE STACKED ARRANGEMENT

Parameter	VVC	M-INV	G-INV
Max current (A)	300		
Continuous output current (Arms)		210	100
Power loss per IGBT chip (W)	261.5	253.5	194
Power loss per FRD chip (W)	155.5	66.5	57
Coolant	50% glycol in water		
Coolant inlet temperature (°C)	70		
Coolant flow rate (L/min)	10		
Maximum coolant pressure drop (bar)	0.2		

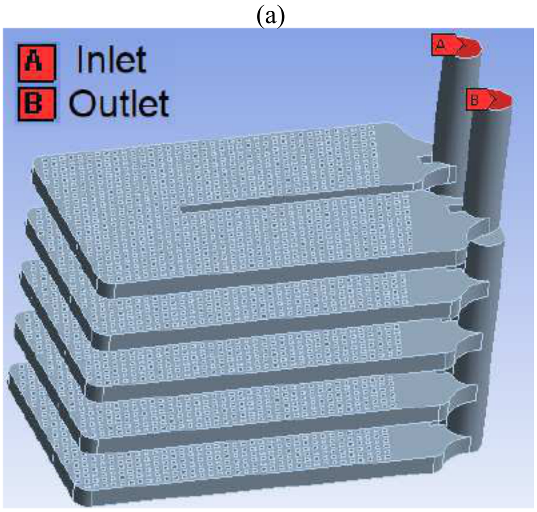
B. *Materials and Bonding Technologies*

The two substrates in each of the four IGBT modules are 0.3/0.32/0.3 $Cu/Si_3N_4/Cu$ substrates because of sufficiently high thermal conductivity and good thermo-mechanical reliability [7]. The conductive shims are made of 1/4/1 Cu/Mo/Cu sandwiched structure, which has coefficients of thermal expansion compatible with IGBT and FRD chips [8]. All the power and signal/control terminals are made of oxygen-free copper (OFHC) with high thermal and electrical conductivities. All the IGBT/FRD chips, conductive shims and terminals may be bonded on or under the conductive tracks of the two substrates or the conductive shims may be bonded on the IGBT/FRD chips with near eutectic Sn-Ag-Cu (SAC) solder joints and the conventional reflow soldering process. All the IGBT/FRD chips may be bonded on the conductive tracks of the bottom substrate, and all the conductive shims may be bonded under the conductive tracks of the top substrate with Ag sintering process for comparison. The five heat sinks and their connectors are made of aluminium alloy for low weight and cost. They are also assumed to be made of copper for comparison. The TIMs between each IGBT module and its two neighbouring heat sinks are 0.2 mm thick graphite sheets with the thermal conductivity higher than those of typical thermal greases.

C. *Structure and Connection of Heat Sinks*



(a)



(b)

Fig. 3. The coolant domains in the stacked arrangement with: (a) U-shaped channel heat sinks; (b) pin fin heat sinks.

It is critical to design the structure and connection of the heat sinks for achieving good cooling performance while remaining low coolant pressure drop across and the inlet and outlet. For demonstrating this, the heat sinks with U-shaped channels and narrow connectors and the heat sinks with pin fins and wide connectors are considered and compared. Fig. 3 shows the coolant domains in the stacked arrangement with these two types of heat sinks. To meet the height requirement of the stacked arrangement, each of the five heat sinks is fixed to 8 mm in total thickness where the top and bottom cold plates are both 2 mm in thickness and the U-shaped channels or the fin fins are 2 mm in thickness or height. The simulation results from the U-shaped heat sinks are presented as one example of poor design of the heat sinks. For the pin fin heat sinks, the pin fins with cylindrical and diamond shapes, different size, angle and orientation were considered and compared. Only the simulation results from the optimised pin fin heat sinks with a specified size, angle and orientation are presented below.

IV. Thermal-Electric and CFD Co-Simulation

A. Modeling Description

Steady thermal-electric and computational fluid dynamics (CFD) coupled simulation was carried out using the system coupling method of Ansys Workbench. In the thermal-electric model, the entire stacked structure is considered, except for the two top and bottom clamping plates and the moulded encapsulants in the four IGBT modules. The thermal-electric loads include the power losses of the IGBT/FRD chips and the currents for the VVC, M-INV and G-INV as specified in Table I. The power losses are applied as surface heat sources on the corresponding IGBT and FRD chips, and the currents are applied as in and out currents on the corresponding DC+, DC- and AC terminals in the four IGBT modules.

In the CFD model, the coolant of 50% glycol in water occupies the flowing channels and connectors of the five heat sinks which are connected in parallel. Turbulent flow is assumed, and the most common K-epsilon (k-ε) turbulence model is employed. The inlet of the coolant is set to have a velocity corresponding to a total flow rate of 6, 8, 10 or 12 L/min entering the five heat sinks. The kinetic energy k, dissipation rate ε and the feed temperature of 70 °C are applied at the inlet boundary, and zero pressure is applied at the outlet boundary. The system coupling region is the interface between the solid structure and the coolant in the thermal-electric and CFD models.

B. Coupled Simulation Results

Figs. 4 to 12 present the representative coupled simulation results. Figs 4 to 11 compare the cooling performance of the stacked arrangements with the U-shaped channel and the optimised pin fin heats sinks where in both cases all the five heat sinks are made of Al alloy and all the four IGBT modules are assembled with SAC solder joints. Fig. 12 further compares the cooling performance of the stacked arrangements with the optimised Al alloy and Cu pin fin heat sinks where in both cases all the four IGBT modules are assembled with the sintered Ag joints to attach all the IGGBT and FRD chips on the bottom substrates and bond all the conductive shims under the top substrates.

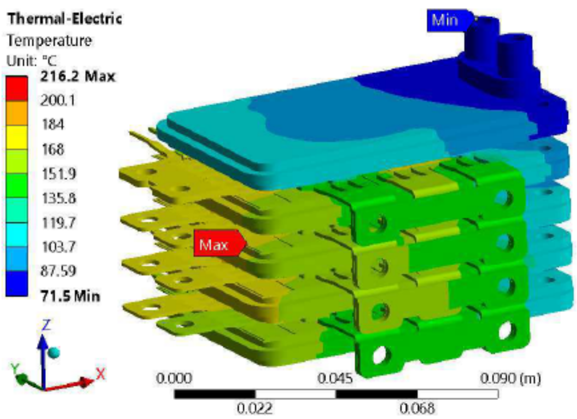


Fig. 4. The simulation result of the temperature filed in the stacked arrangement with the U-shaped channel heat sinks under the flow rate of 10 L/min for the coolant.

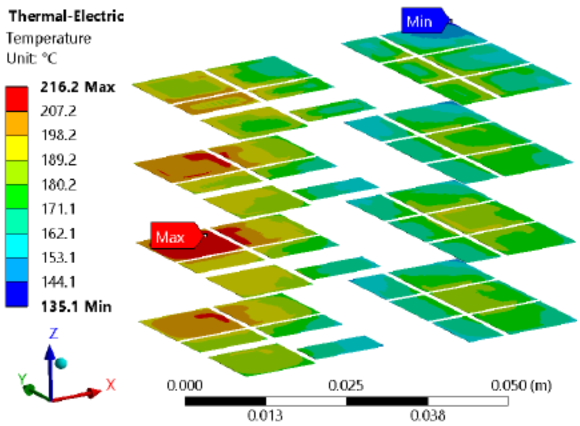


Fig. 5. The simulation result of the temperature filed in all the IGBT and FRD chips in the stacked arrangement with the U-shaped channel heat sinks under the flow rate of 10 L/min for the coolant.

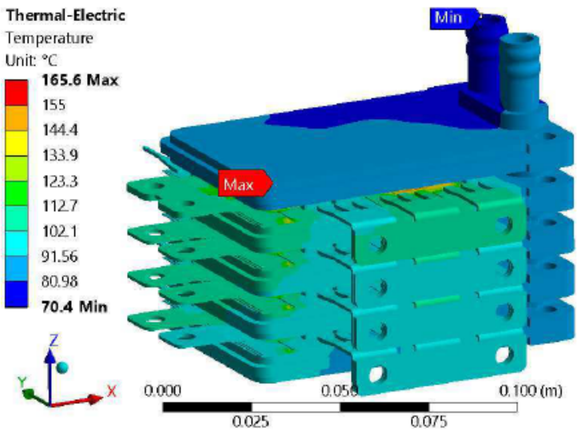


Fig. 6. The simulation result of the temperature filed in the stacked arrangement with the optimised pin fin heat sinks under the flow rate of 10 L/min for the coolant.

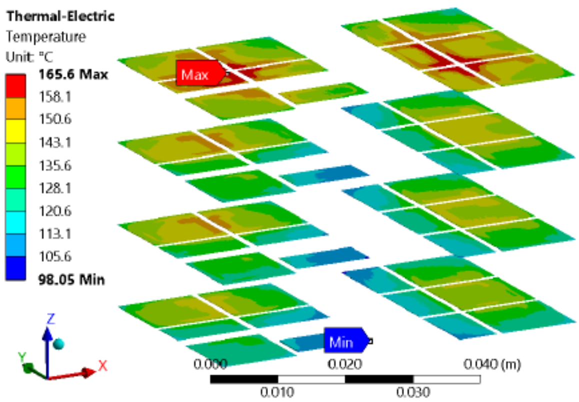


Fig. 7. The simulation result of the temperature filed in all the IGBT and FRD chips in the stacked arrangement with the optimised pin fin heat sinks under the flow rate of 10 L/min for the coolant.

In Figs 8 and 11, Tnode,max stands for the maximum node temperature, and Tvj,max stands for the maximum virtual junction temperature of the IGBT and FRD chips in the four IGBT modules of the corresponding stacked arrangement. The virtual junction temperatures were estimated from the average temperature on the active regions of the three paralleled IGBT or FRD chips in the half bridge switch for the VVC, the two paralleled IGBT or FRD chips in the three half bridge switches for the M-INV, or each IGBT or FRD chip in the three half bridge switches for the G-INV [9]. In Fig. 9, Tnode,max stands for the maximum node temperature in the coolant domain where the coolant flows to cool the corresponding stacked arrangement.

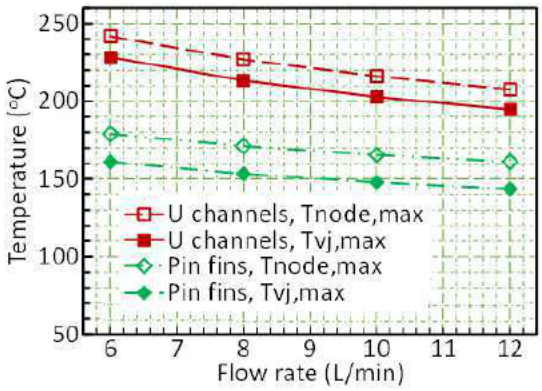


Fig. 8. Comparison of the maximum node and virtual junction temperatures with respect to the flow rate of the coolant in the stacked arrangements with the U-shaped channel and the optimised pin fin heat sinks.

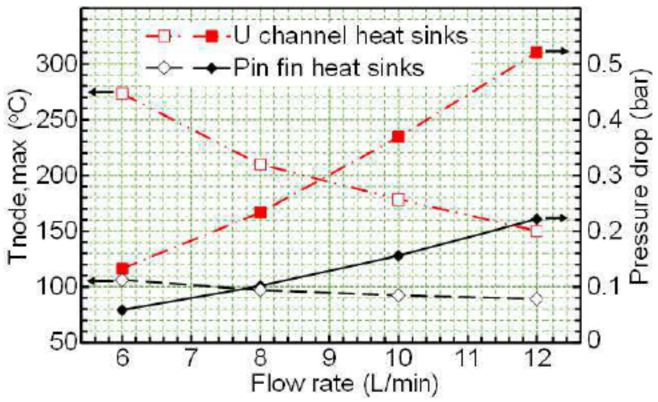


Fig. 9. The maximum node temperature in the coolant domain and the pressure drop across the inlet and outlet of the coolant in the stacked arrangements with the U-shaped channel and the optimised pin fin heat sinks.

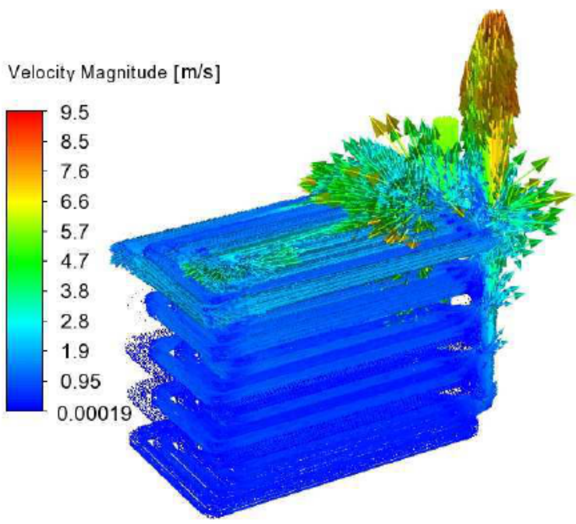


Fig. 10. The simulation result of the velocity magnitude in the coolant domain in the stacked arrangement with the U-shaped channel heat sinks under the flow rate of 10 L/min for the coolant.

The coupled simulation results reveal that the U-shaped channel heat sinks in the stacked arrangement have very poor cooling performance, leading to the maximum virtual junction temperature which is much higher than 150 °C and the pressure drop is remarkably higher than 0.2 bar under the flow rate of 10 L/min. In particular, the virtual junction temperatures of the IGBT switches which have lower power losses in the three IGBT modules for the M-INV appear to be higher than the virtual junction temperatures of the two corresponding IGBT switches which higher power losses in the top IGBT modules for the VVC. This can be attributed to the fact that the channels in the connectors to connect the five U-shaped channel heat sinks in parallel are rather narrow and the flow resistance of the coolant through the top to the bottom heat sinks increases noticeably, resulting in reduced flowing velocities and thus reduced flow rate of the coolant through from the top to the bottom heat sinks, see Fig. 10.

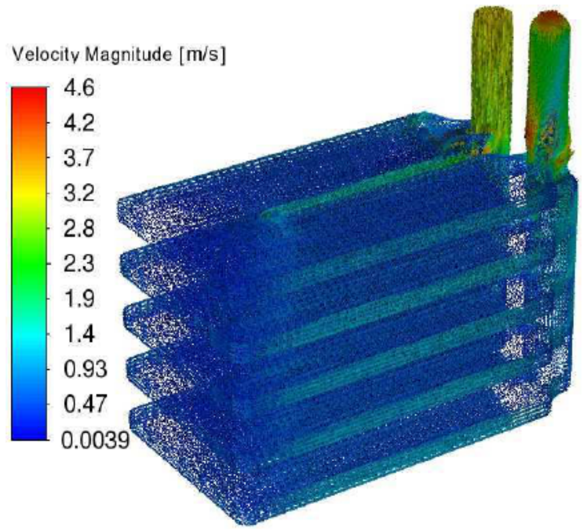


Fig. 11. The simulation result of the velocity magnitude in the coolant domain in the stacked arrangement with the optimised pin fin heat sinks under the flow rate of 10 L/min for the coolant.

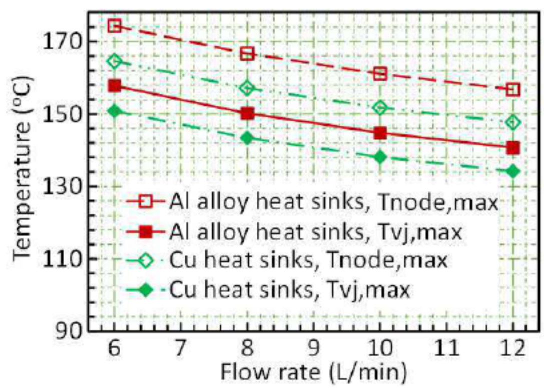


Fig. 12. The maximum node and virtual junction temperatures with respect to the flow rate of the coolant in the stacked arrangements with the IGBT modules assembled the sintered Ag joints and the optimised pin fin heat sinks made of Al alloy and Cu.

By modifying the channels in the connectors to connect the five paralleled heat sinks and optimising the orientation of pin fins in the pin fin heat sinks, the pressure drop across the inlet and outlet can significantly be reduced, and the flow rates of the coolant through the five heat sinks become quite consistent, see Figs. 9 and 11. As a result, the maximum virtual junction temperature occurs in the three paralleled low side FRD chips, followed by the virtual junction temperature in the three paralleled low side IGBT chips of the top IGBT module for the VVC which have higher power losses than the FRD and IGBT chips in the other three IGBT modules for the M-INV and G-INV. In particular, the coupled simulation result of the maximum virtual temperature in the stacked arrangement with the optimised pin fin heat sinks can be lower than 150 °C under the coolant feed temperature of 70 °C, flow rate of 10 L/min and pressure drop of 0.16 bar.

The cooling performance of the stacked arrangement under the different simulation cases may be compared with a thermal resistance defined as Rth=(Tvj,max-70)/P where P is the power loss which is the same value for all the cases. Comparing Figs. 8 and 12, it can be seen that replacing the SAC solder joints with sintered Ag joints in the four IGBT modules, the Rth of the stacked arrangement can be reduced about 2%, and further replacing the heat sink material of Al alloy with Cu, the Rth of the stacked arrangement can be reduced 6.3% to 6.6% under the flow rate from 6 to 12 L/min. The limited improvement in the cooling performance by the sintered Ag joints and the Cu heat sinks can be ascribed to the TIMs between the IGBT modules and their adjacent heat sinks which contribute relatively high thermal resistance.

V. Experimental Validation

A. Prototyping processes

The designed IGBT modules have successfully been prepared with the following assembling processes: (i) a reflow soldering process to attach the IGBT/FRD chips and NTC thermistor on one bottom substrate, and bond all the conductive shims on the turned upside down top substrate for each IGBT module; (ii) a ultrasonic bonding process to bond the Al wires to interconnect the gate pads of the IGBT chips and the corresponding conductive tracks of the bottom substrate attaching the IGBT/FRD chips and NTC thermistor; (iii) a second reflow soldering process to bond all the power and signal/control terminals and the other sides of all the conductive shims on the conductive tracks of the bottom substrate attaching the IGBT/FRD chips and NTC thermistor or on the top sides of these IGBT/FRD chips; and (iv) a moulding process to inject and form the epoxy compound encapsulant for each IGBT module.

However, the delivery of the custom-made heat sinks has been delayed by the supplier. Once the heat sinks are received, each sample of the stacked arrangement will be produced with a mounting process to stack four IGBT module and five heat sinks together with eight pieces of graphite sheets, two clamping plates attaching the compliant pads and 4 pairs of M6 screws and nuts.

B. Thermal test

After the samples of the stacked arrangement are produced, transient thermal test will be carried out using a Mentor Graphics® 1500A power tester and a recirculating chiller to deliver the coolant of 50% glycol in water into the five paralleled heat sinks. The electrothermal generation in such thermal test cannot be adjusted to match the values specified in Table I for the above thermal-electric and CFD coupled simulation. This is because the values in Table I include both conducting losses and switching losses of the IGBT and FRD chips based on the operation of the electric control system where the VVC delivers 100 kW, the M-INV delivers 100 kW and the G-INV delivers 50 kW. In the transient thermal test using the Mentor Graphics® 1500A power tester which is equipped in our laboratory, only the conducting losses of the IGBT and FRD chips can be used as the heat sources.

Nevertheless, the transient thermal test results can still be compared with additional thermal-electric and CFD coupled simulation based on the testing condition and the electrothermal generation during the test. If the additional simulation results satisfactorily agree with the test results, this will demonstrate that the thermal-electric and CFD models and the electrical and thermophysical properties of all the materials in the models are sufficiently accurate for the electrothermal and cooling analysis, and thus validate the above thermal-electric and CFD coupled simulation results to support the thermal design of the stacked arrangement.

VI. Conclusions

The stacked arrangement inserting four IGBT modules between five heat sinks can be designed into a compact 121 mm × 94.7 mm × 90.8 mm structure for the variable voltage converter delivering 150 kW, the motor inverter delivering 100 kW and the generator inverter delivering 50 kW.

Thermal-electric and CFD coupled simulation results indicate the maximum virtual junction temperature in the four IGBT modules can be below 150 °C under the worst electro-thermal generation, the coolant feed temperature of 70 °C, flow rate of 10 L/min and pressure drop of 0.16 bar.

Replacing the SAC solder joints with sintered Ag joints in the four IGBT modules and replacing the heat sink material of Al alloy with Cu can somewhat but not very effectively improve the cooling performance of the stacked arrangement which is limited by the thermal interface materials.

Experimental validation of the coupled simulation results has been delayed, and hopefully it will be obtained and presented at the conference. If validated, the stacked arrangement can be used to increase power density and improve electrical and thermal performance of the power modules in the electric control systems with multiple converters/inverters.

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