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Immersed and integrated converter (30 kW) for fuel cell system in aircraft application

Integrated systems typically use several independent subsystems from different manufacturers connected to each other. To improve power density, some subsystems can be advantageously designed together. In the case of a hybrid system combining a fuel cell and a battery, the DC/DC converter dedicated to adjusting the voltages of the power sources can be coupled within the stack and share the cooling circuit.

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“Smart fuel cell” technology

To hybridize a fuel cell and a battery, a DC/DC converter is typically used to adapt the output voltage of the fuel cell. To optimize the power density of both subsystems, the converter can be integrated on an end plate of the stack and can use the same cooling circuit as the fuel cell. The system called “smart fuel cell” also integrates the monitoring of the stack. The filtering and connection between the subsystems are optimized through their integration. Several smart modules can be connected in parallel to increase the available power for the targeted application that allows keeping a good efficiency.

This development is part of a European research project (Flhysafe) which consists to provide emergency power on an aircraft. This project has received funding from the Clean Hydrogen Partnership under Grant Agreement No 779576. This Joint Undertaking receives support from the European Union’s Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe Research.

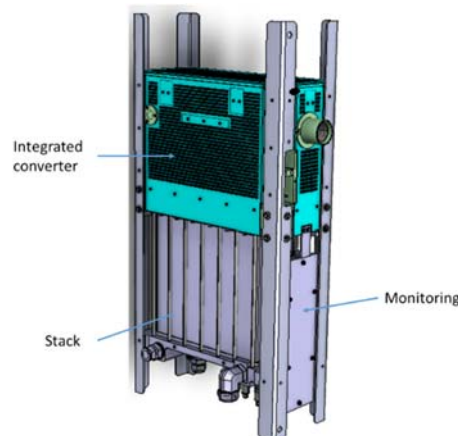


Figure 1: “Smart fuel cell” technology

DC/DC converter design

The integrated converter adapts the output voltage of the fuel cell (180 V to 220 V in steady-state) to the internal Direct Current (DC) bus voltage (500 V to 560 V in steady-state). To save weight in the developed system, a non-isolated converter is designed and the fuel cell stack is insulated from the metal frame of the system. The converter is based on a 12-phase interleaved boost converter. The input ripple current applied to the stack is thus reduced and the input/output capacitances are minimized. A field programmable gate array associated with a microcontroller controls the high number of phases at the expected operating frequency (100 kHz). The input current or the output voltage can be controlled. The switches are commercial Silicon Carbide (SiC) modules (Wolfspeed). The twelve inductors are based on a specific development (68 μ H per phases, Exxelia). A ring core is used with a single layer of conventional wire (one strand). This optimizes the cooling and avoids the risk of overheating the wiring. Precautions had to be taken regarding the materials compatibility with the cooling fluid (Nycodiel).

The converter is cooled by the same cooling circuit as the fuel cell stack. An efficient and custom solution, a cooling box, removes heat by a dielectric fluid from the immersed passive devices and the baseplates of power semiconductor modules. The input power supply is also mounted on the cooling box.

In order to comply with the tradeoff between the pressure drop of the cooling box (175 mbar) and the operating junction temperature of the MOSFETs (120°C), the current supplied by the fuel cell must be limited to 175 A, which corresponds to a converter output power of 30 kW. This power could be increased if the voltage of the fuel cell is increased.

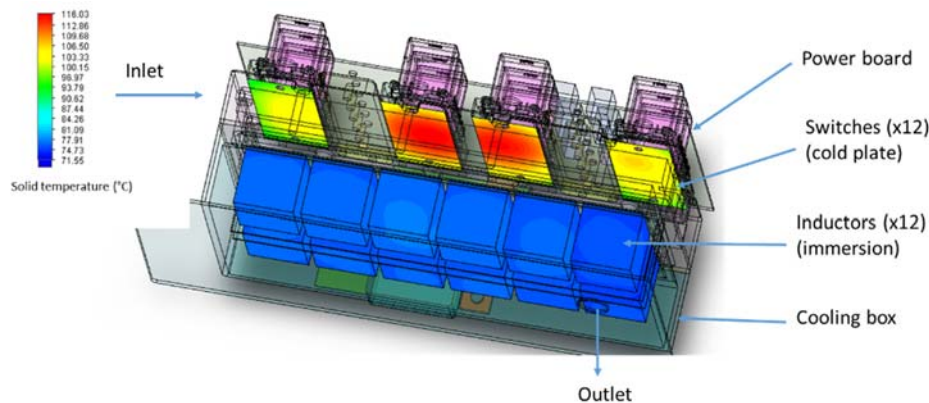


Figure 2: Cooling of the SiC modules and inductors

DC/DC converter manufacturing and assembling

To fit the area of the end plate, four electronic boards are mounted around the cooling box. The electrical connections between the power board and the control board are numerous (96). To mitigate the effect of bad connections using wires, board-to-board connectors are used. The number of connectors is thus reduced. The input board integrates the input filtering and the main power supply. The input current sensor is electrically connected to this board. The output board integrates part of the output filtering and the output current sensor. The SiC modules, gate drivers and phase current measurements are present on the power board. The control board integrates the programmable integrated circuits. The communication and voltage measurements

(input and output), the electrical isolation of the gate drivers, and the hardware protections are also implemented on this board.

The cooling box is made by machining an aluminum alloy (6061 T6) with a high thermal conductivity (167 W/m.K at 20°C). Four insulated and waterproof feedthroughs connect electrically the inductors and the electronic boards or the bus bars. Nitrile seals ensure the tightness. The cover of the cooling box integrates channels to evacuate switch losses. The thermal resistance per module is efficient (less than 0.1 °C/W). To share the coolant inside the cooling box, two plates are used. The first one divides the coolant between the modules and the inductors. The second one divides the coolant through the different inductors.

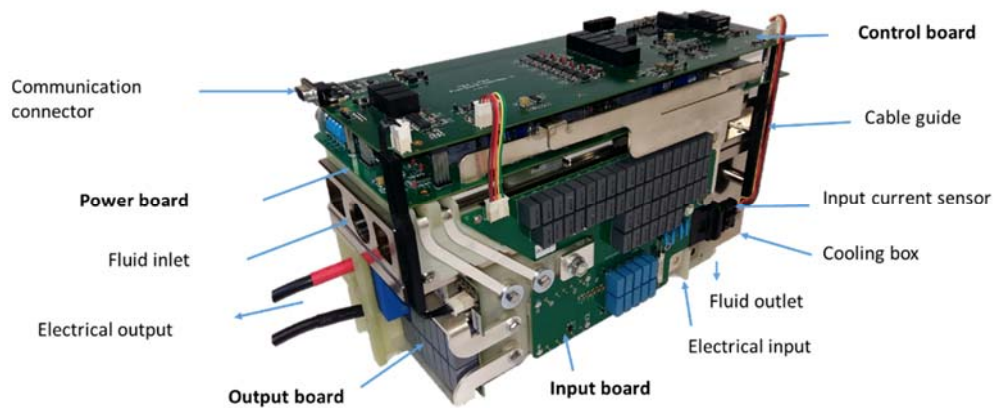


Figure 3: Integrated immersion-cooled converter

The area of the converter is 585 cm². For a height of 27 cm, the volume is 16 L. The mass is close to 19.5 kg. The volume and the mass do not take into account the housing and the coolant. To improve performance in terms of vibration and shock, mechanical parts have been designed such as pads to hold the boards together and stiffeners to hold the stack with the converter. The heavy inductors are also clamped by holding parts inside the cooling box.

DC/DC converter tests

The converter complies with most of the electrical, thermal, mechanical and fluidic requirements.

In terms of electrical requirements, the efficiency of the converter is approximatively 96.5% from an output power of more than 10 kW and an output voltage of 540 V. Hard switching is used and the SiC MOSFETs have been slowed down to match the conducted emissions on the power wires. Efficiency could be improved by increasing the switching speed of the MOSFETs despite a likely higher level of conducted noise or larger filtering. In operation, a duration of 1 s is required to provide the application load steps (from 2 kW to 21 kW or from 21 kW to 30 kW). This duration complies with the dynamic of the fuel cell. The output voltage ripple is limited to 510 mV for an output power of 30 kW (worst case). This amplitude is less than 0.1% of the supplied voltage. A duration of 350 ms is necessary to start the converter.

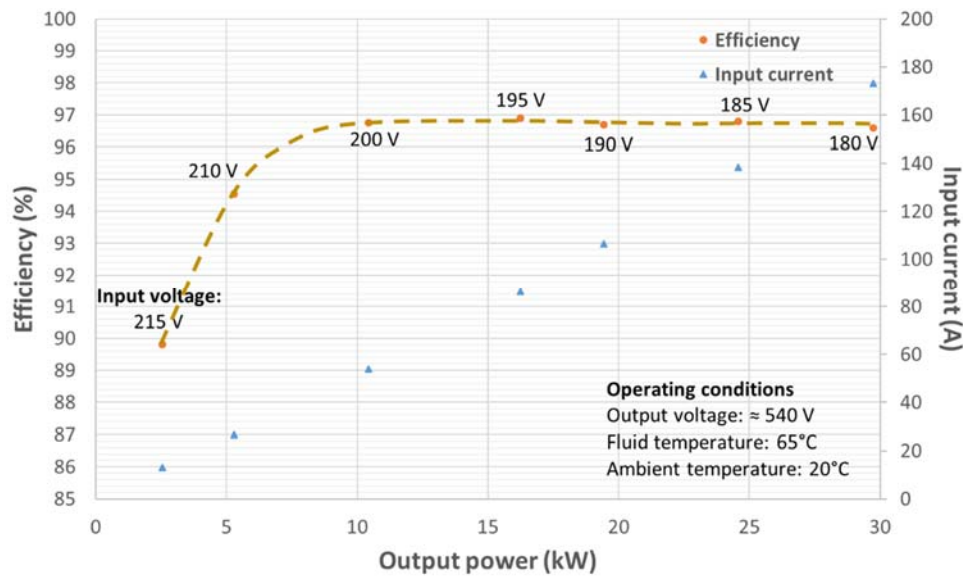


Figure 4: Efficiency of the prototype

Conclusion

To improve the power density of a fuel cell system, a “smart fuel cell” technology has been developed to integrate the stack, a non-isolated DC/DC converter and monitoring together. The filtering and connection between the subsystems are thus optimized through their integration. The area available on the end plate led to the development of a DC/DC converter with an unusual form factor. The electronic devices and boards are mounted outside of a cooling box. The cooling box is specially designed to remove heat from devices inside by dielectric fluid immersion, inductors, and the devices outside, switches.

Integration of the converter into the fuel cell, which is being developed by Safran as part of the project, is scheduled for early 2022. Functional and environmental tests will then be carried out at INTA in Spain, among other facilities.