A Cryogenically-Cooled MW Inverter for Electric Aircraft Propulsion

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Power electronic converter will be a key enabler for future electrified aircraft propulsion system. In aircraft applications, superconducting technologies such as superconducting motors and generators along with supporting power systems will grow in importance. Utilizing cryogenic cooling for power converter potentially can significantly improve the inverter system efficiency and specific power. This paper presents the cooling, hardware, and testing of a cryogenically-cooled MW inverter developed for electrified aircraft propulsion system. The 1 MVA full load testing with cryogenic cooling is demonstrated. The developed inverter system achieves 18 kVA/kg specific power and 99% efficiency, which provides a promising solution to achieve high power density and efficiency for future electrified aircraft propulsion system.

I. Introduction

Hybrid power generation and distributed propulsion power has been identified as candidate transformative aircraft configurations for future commercial transport vehicles with reduced fuel burn and harmful emissions. The high power inverter will be a key enabler for future electrified aircraft propulsion as envisioned by NASA and Boeing [1]. At system level in aircraft applications, superconducting technologies such as superconducting motors/generators along with their supporting power systems will grow in importance. Integrating the associated power electronics with the superconductive motor/generator systems can avoid extra thermal insulation and temperature regulation system, and reduce system complexity and improve power density. Several power semiconductor devices, such as silicon (Si) and gallium nitride (GaN), have lower specific on-state resistance and faster switching speed at cryogenic temperature, resulting in reduced loss. Resistivity of conductors, such as cooper and aluminum, is significantly reduced at cryogenic temperature, leading to less usage of inductor windings and busbars required in a power converter. However, there have not been many reports about power converters at cryogenic temperatures and the reported power level is relatively small [8-11]. Moreover, there is no specific detailed cooling system design provided that would be suitable for high power electronics applications.

In [2], the design of a cryogenically-cooled MW inverter for electrified aircraft propulsion system is presented. Experiment results at ambient temperature are provided to verify the basic functionality of the inverter system. The inverter is DC-fed from ±500 V bus and capable of three-phase output up to a fundamental frequency of 3 kHz. The inverter system architecture is shown in Fig. 1, which includes DC-link capacitor, power stage, input/output filter, gate drive, protection, control, and thermal interface with a cryogenic cooling system. The MW inverter utilizes a three-level active neutral point clamped (3L-ANPC) inverter topology and a phase-leg of the 3L-ANPC circuit scheme is shown in Fig. 2(a). Fig. 2(b) shows the inverter system. Two 500 kW inverters are paralleled and interleaved through coupled inductors to achieve 1 MW power while reducing harmonics ripples. DC and AC side electromagnetic interference (EMI) filters are employed to suppress EMI noise and meet DO-160 EMI standards [7].

Furthering the work presented in [2], this paper conducts the design and full power testing with cryogenic cooling of this 1 MW inverter. The inverter system cooling strategy, hardware and integration, full power testing results with cryogenic cooling are illustrated. Testing results show that the developed inverter provides a promising solution to achieve high power density and efficiency for future aircraft propulsion system.

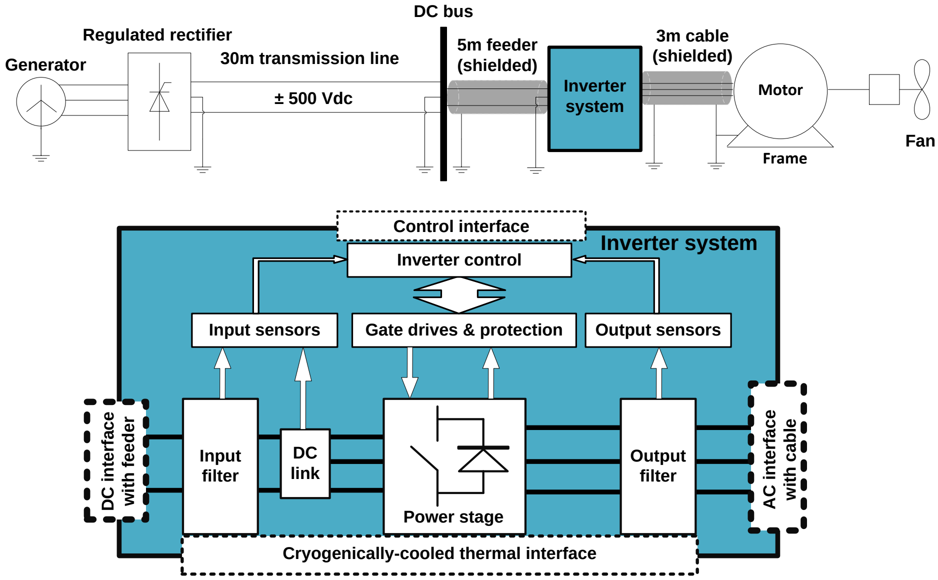
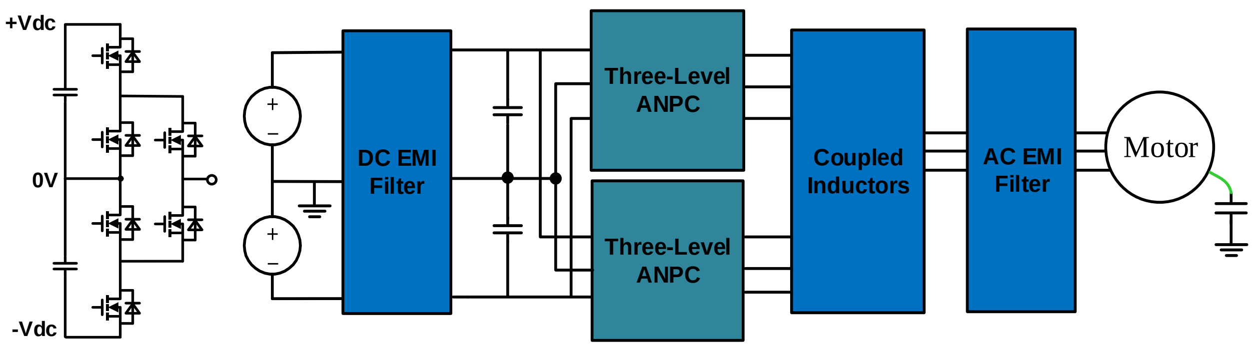


Fig. 1. Inverter system architecture.



(a) (b)

Fig. 2. (a) Phase-leg of 3L-ANPC inverter, (b) The 3L-ANPC based 1 MW inverter system.

II. Inverter System Cooling Strategy

The power semiconductor device characterization including Si MOSFET, SiC MOSFET and GaN HEMT were conducted in [3-5]. The results show that both Si and GaN devices have lower specific on-state resistance and faster switching speed at cryogenic temperature while SiC devices on-state resistance increases going from room temperature to cryogenic temperature. SiC and GaN devices show stable breakdown voltages while the breakdown voltage of Si devices trend down as temperature decreases. Although Si MOSFET and GaN HEMT devices show better performance at cryogenic temperature, high current power module for Si MOSFET or GaN HEMT to support a MW inverter for cryogenic operation is not yet available. In addition, none of the commercial module packaging technologies are suitable for cryogenic operation. Therefore, the 900V/800A SiC power module from Wolfspeed is selected in this design to support 1 MW power delivery.

Fig. 3 shows a picture of the selected power module and Fig. 4 shows the tested on-state resistance as a function of temperature. The lowest on-state resistance occurs when the temperature is around 275K. It is preferred that the power module could operate at this temperate at half load condition. The power module cannot be cooled to a temperature below 223K otherwise the silicone gel used for module packaging could be damaged.

With these considerations, cold nitrogen gas cooling instead of direct liquid nitrogen cooling is adopted for power stage. Fig. 5 shows the cooling concept. The nitrogen gas will go through coils which are submerged into a liquid nitrogen bucket. By adjusting the height of the jack, the number of turns of the coils that are submerged into liquid nitrogen can be adjusted. The cooling performance of gaseous nitrogen system can be controlled by adjusting the flow rate of the gas through a regulator combined with adjusting the number of coils turns submerged in the liquid nitrogen. Fig. 6 shows the designed modular cold plate for a phase leg. In total, six cold plates ae included in the inverter system. Tapered fins are used in the cold plate channel to provide a uniform temperature distribution of all the dies on an individual module. The cold plate has three independent cooling channels for three power modules with different loss budgets. The flow rate of the gas nitrogen can be tuned separately with the valves as shown in Fig. 6.

Fig. 3. 900V/800A SiC power module from Wolfspeed.

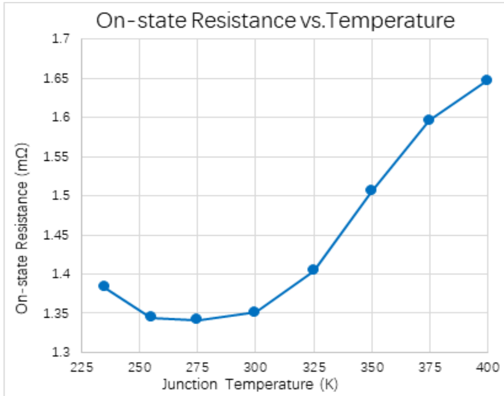


Fig. 4. On-state resistance of the power module.

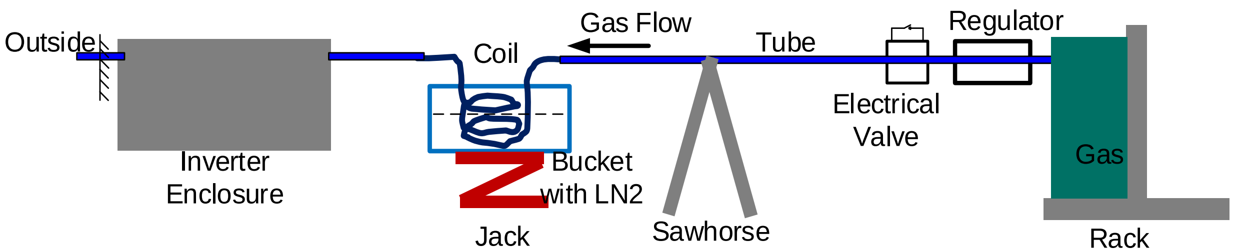


Fig. 5. Power stage cooling concept.

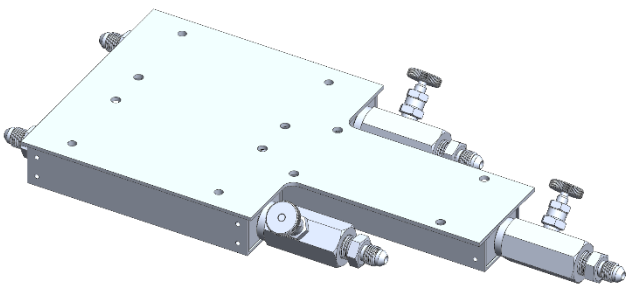


Fig. 6. Modular cold plate.

For EMI filter, the magnetic characterization results in [6] show that both ferrite and nanocrystalline material have reduced permeability and increased core loss at very low temperature. However, the cryogenic temperature could benefit the filter due to the significant reduced resistivity of copper used for inductor winding. Thus, direct liquid nitrogen cooling is adopted for EMI inductors. Nanocrystalline material is selected for the coupled inductors and common mode (CM) inductor in the system. Differential mode (DM) inductors use air core structure due to the relatively low inductance required and to maximize the benefit of cryogenic cooling. The inductors use 3-D printed thermoplastic housing that accommodates liquid nitrogen cooling for the large inductors and to reduce housing weight. Fig. 7 and Fig. 8 show the housing structure of the coupled inductor and CM inductor, respectively.

Thus, the dual gaseous and liquid nitrogen cooling is utilized to accommodate the cooling requirement of both power stage and EMI filter, as shown in Fig. 9. Each inverter power stage has a gas nitrogen path. The AC side inductors, coupled inductors, and DC side CM inductor all share a liquid nitrogen path. There is no mechanical or thermal interference among the electrical busbars and their connections, the liquid nitrogen flow system, and the gaseous nitrogen system.

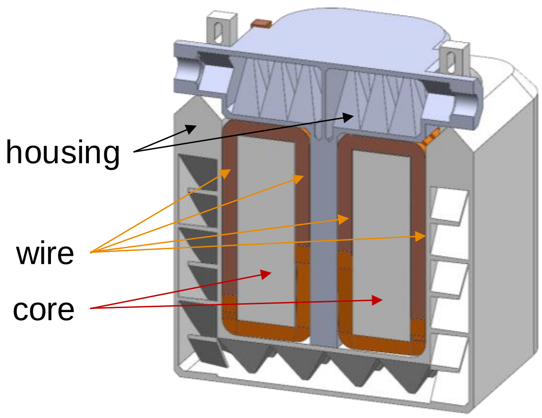


Fig. 7. Housing design of the coupled inductor.

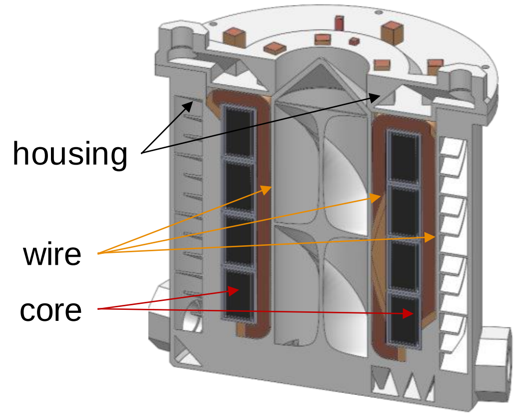


Fig. 8. Housing design of the CM inductor.

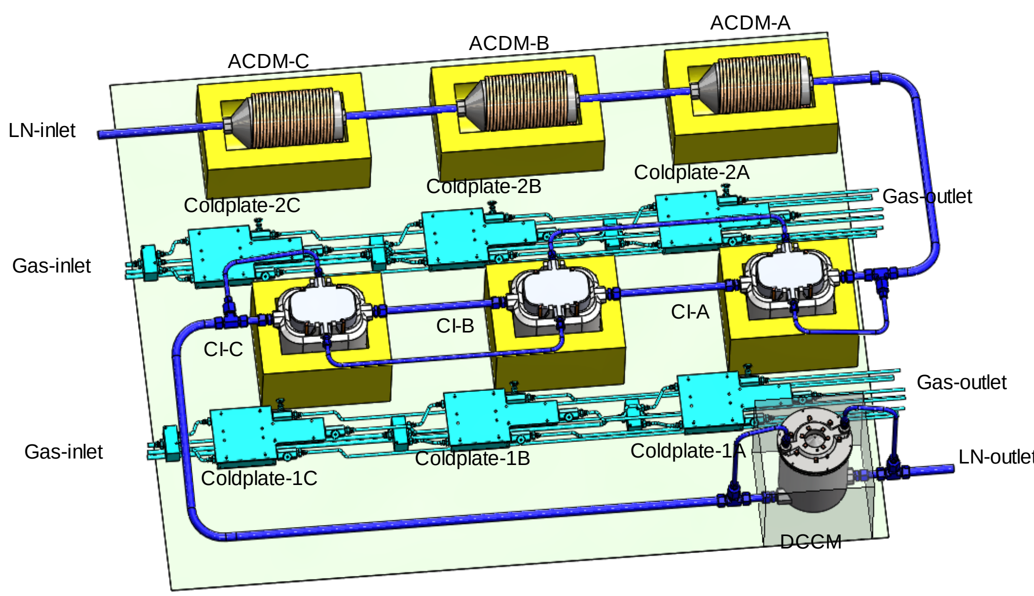


Fig. 9. The dual gaseous nitrogen (GN) and liquid nitrogen (LN) cooling system.

III. Inverter System Hardware and Integration

Fig. 10 shows the prototype of a phase-leg of one 500 kW 3L-ANPC inverter including power module, DC-link capacitors, busbar, gate drive, and isolated power supply. Fig. 11 shows the cold plate for the phase-leg. Fig. 12 and Fig. 13 show the prototypes of the 3D-printing housing based coupled inductor and DC side CM inductor, respectively.

Fig. 14 shows the integration concept of the 1 MW inverter system with enclosure. For the electrical parts, the two inverters are at the middle of the enclosure in parallel. The coupled inductors are located between two inverters. The control board is mounted at the left side of the enclosure. The DC input is at front side of the enclosure while AC output is at the back side. For cooling parts, both the liquid and gas tubes extend from left of the enclosure to the right, with the liquid nitrogen tubes making a serpentine pattern. Thermal insulation made by foam is attached around the tubes, filters, and cold plates to minimize the heat loss.

Fig. 15 shows the inverter hardware inside the enclosure. With the cooling strategy illustrated, Fig. 16 shows the cryogenic cooling system setup outside the enclosure.

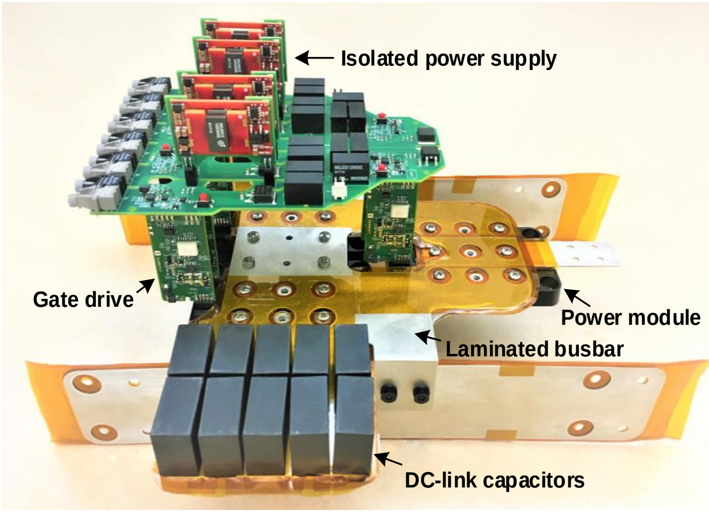


Fig. 10. A phase-leg of the 3L-ANPC inverter.

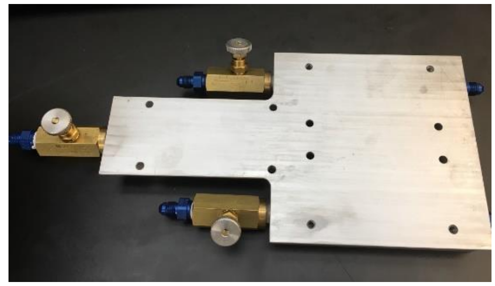


Fig. 11. Cold plate of a phase leg.

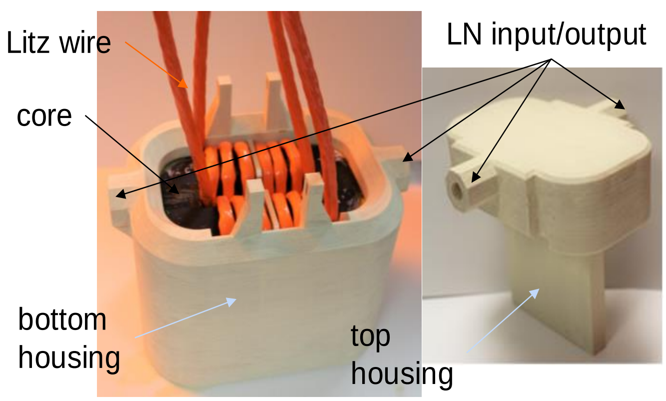


Fig. 12. Coupled inductor with housing.

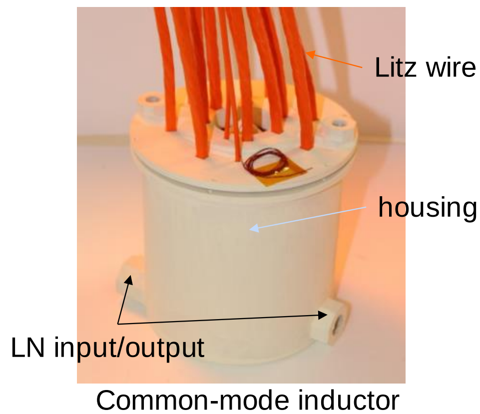


Fig. 13. CM choke with housing.

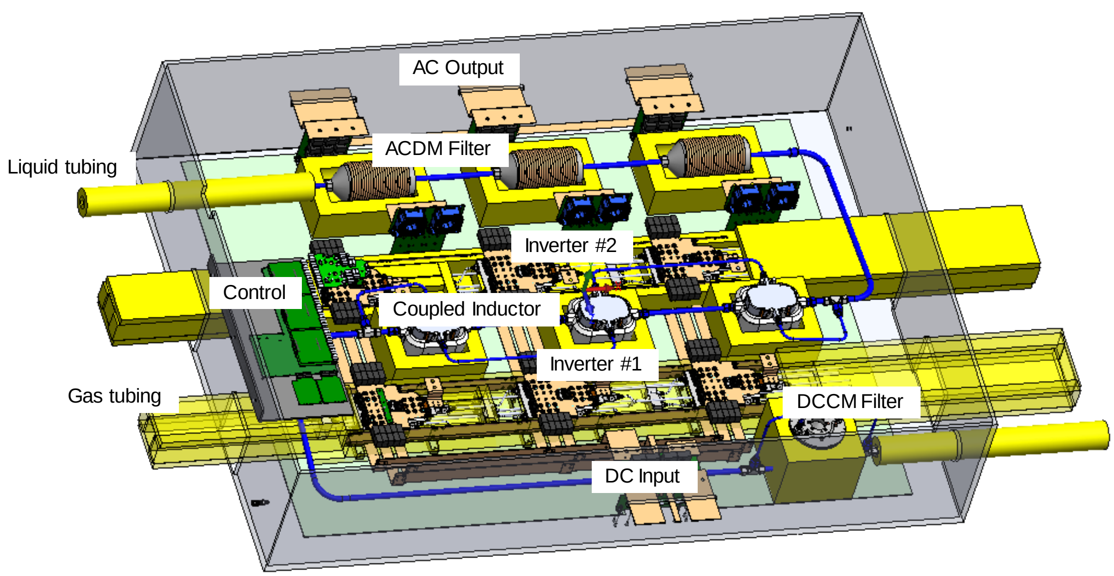


Fig. 14. The integrated inverter system.

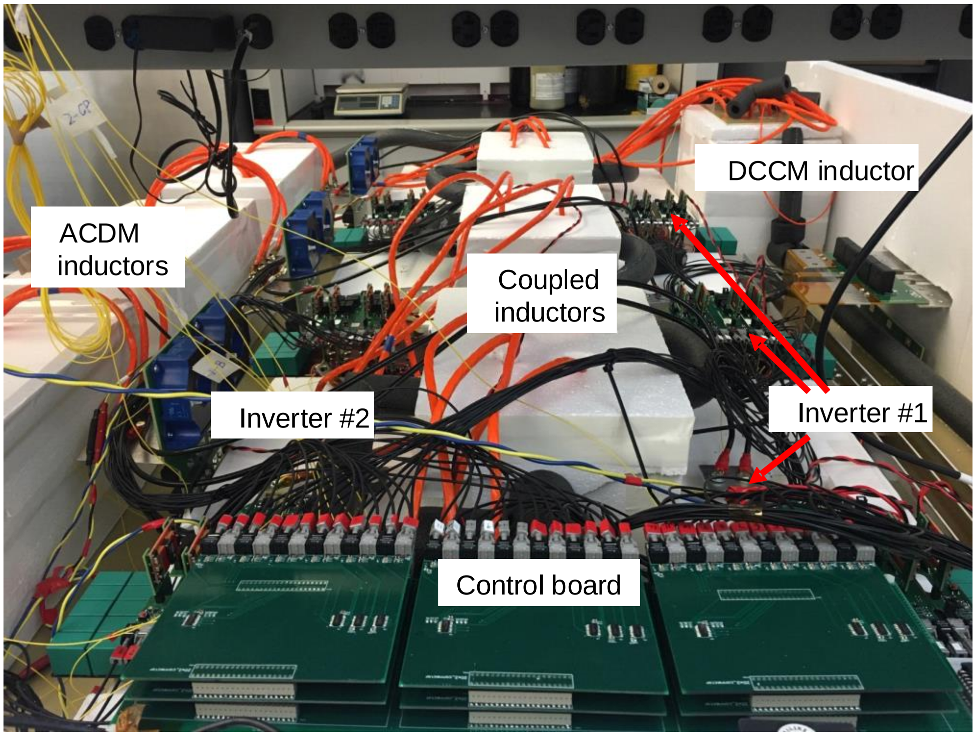


Fig. 15. Inverter hardware inside the enclosure.

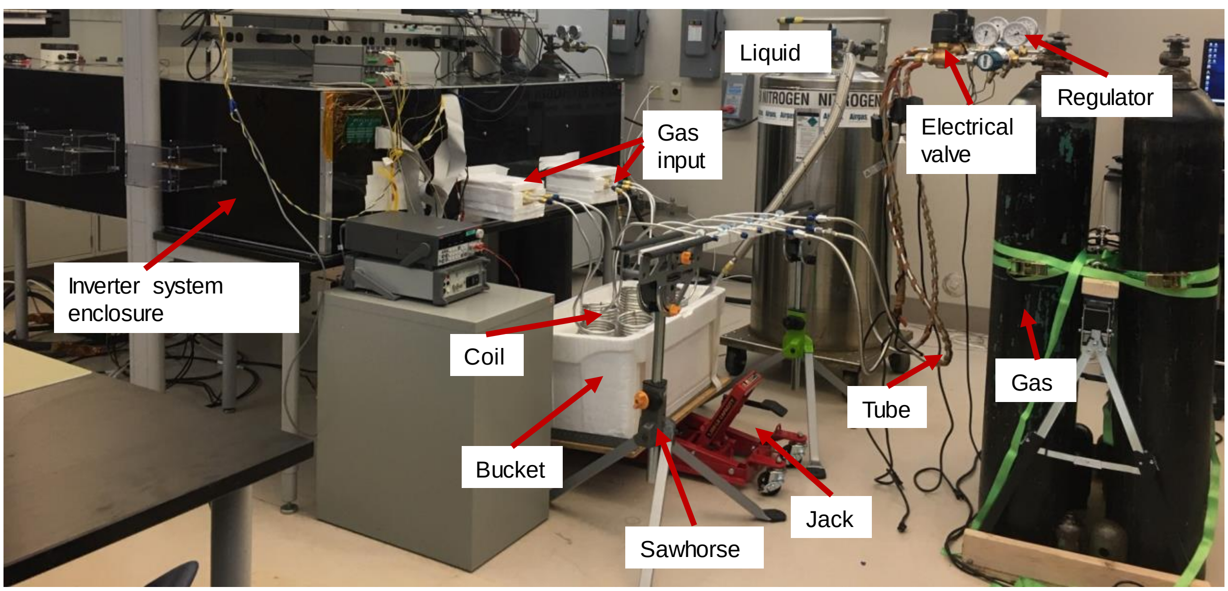


Fig. 16. Cryogenic cooling system setup for the 1 MW inverter.

IV. Inverter System Testing with Cryogenic Cooling

The basic function verification of the developed inverter at room temperature was presented in [2]. This section presents the full power testing of the 1 MW inverter with cryogenic cooling.

First, one 500 kW inverter is tested to full power with cooling setup of Fig. 16. Fig. 17 shows the tested three-phase output current waveform at 1 kV dc voltage input. Rogowski coils are used to measure the large currents. The ratios of the three Rogowski coils used are 2 mv/A, 5 mV/A, and 5mV/A. The measured peak current is around 650 A.

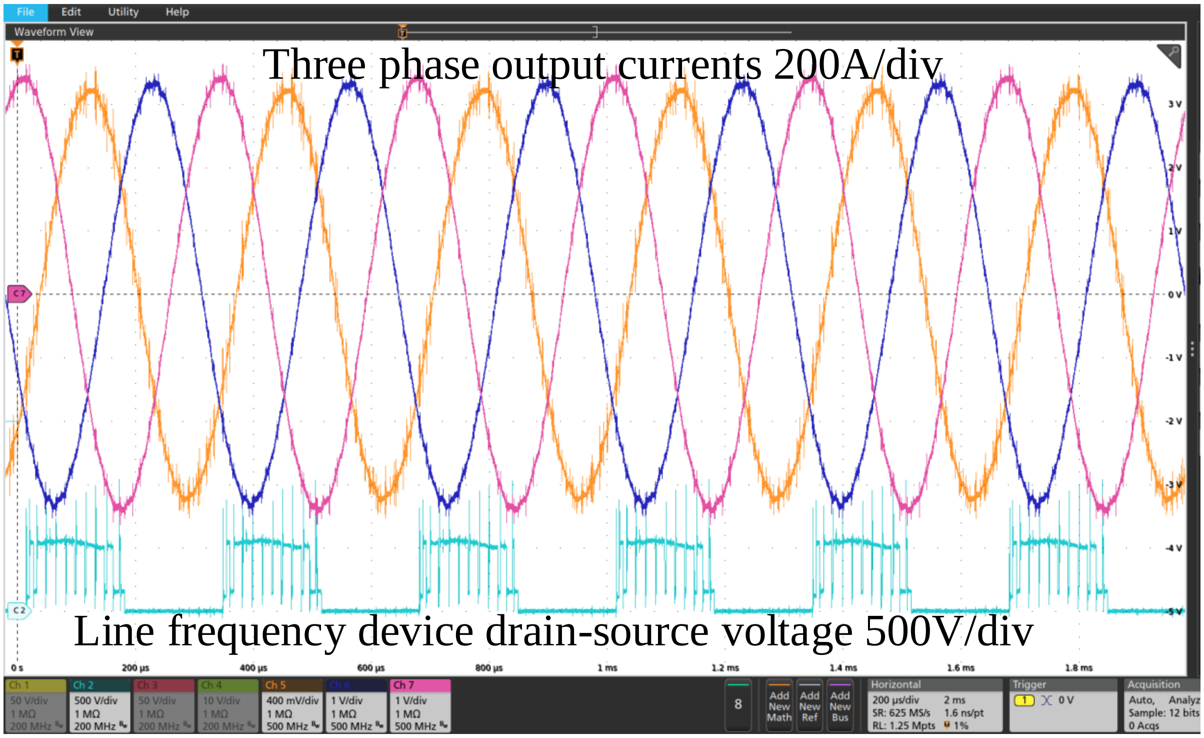


Fig. 17. Tested one 500 kW inverter at full load condition.

Next, two 500 kW inverters paralleling operation is tested at full power. Fig. 18 shows the three-phase current waveforms of the paralleled inverters and a line-to-line voltage waveform. For this test, the AC phase output voltage fundamental frequency components peak voltage is 549 V and AC phase peak current for one inverter is 610 A, and the total apparent power is 1 MVA.

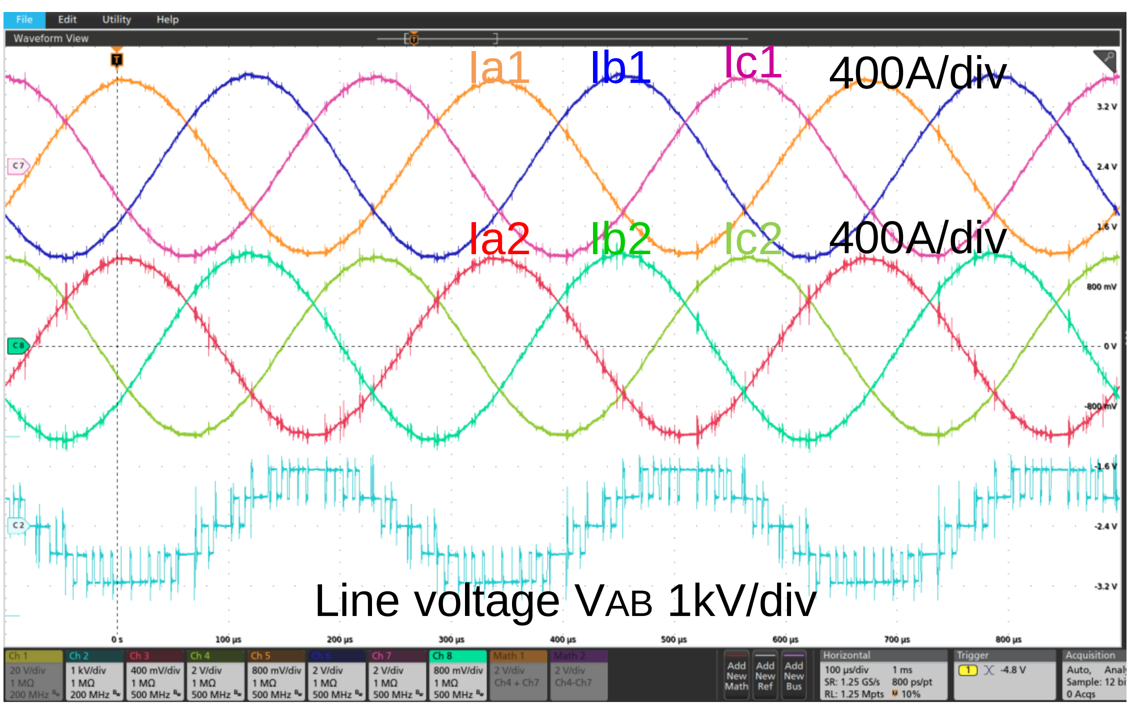


Fig. 18. Tested two inverters paralleling operation at 1 MVA full load.

To demonstrate the current sharing performance between the two inverters, the three-phase currents of the two inverters are put together as shown in Fig. 19. The phase output currents of the two inverters are overlapped with each other, which indicates good current balancing among the two 500 kW inverters. Fig. 20 shows the circulating current between the same phases of the two paralleled inverters, which is almost zero.

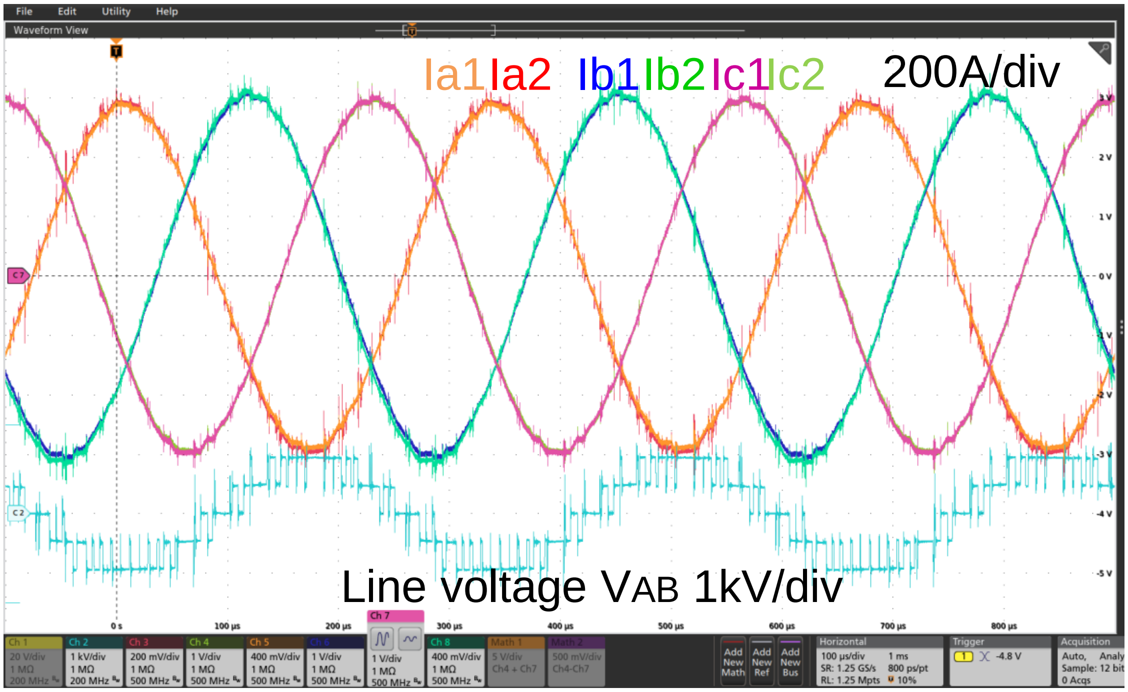


Fig. 19. Tested two 500 kW inverters paralleling at full load.

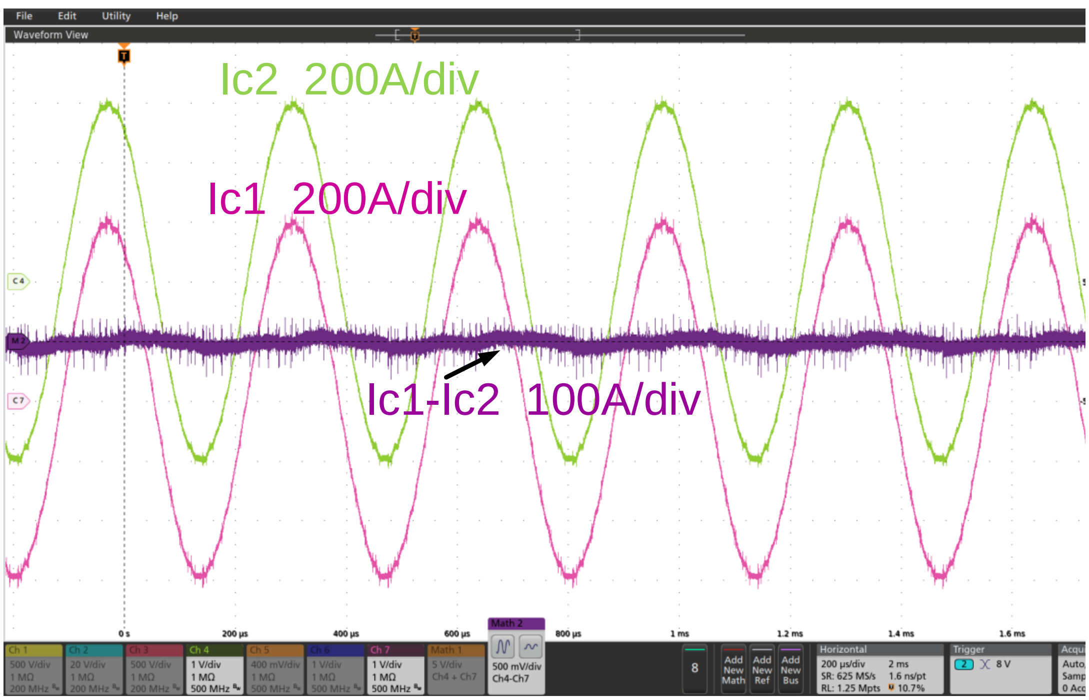


Fig. 20. Tested circulating current of the paralleled two 500 kW inverters.

The MW inverter prototype power loss is tested. Fig. 21 shows the tested power stage losses at different power level and Fig. 22 shows the inverter efficiency data, respectively. It can be observed that the power stage efficiency is

99.2% at half load and 99% at full load. If the filter power loss is considered, which takes around 30% of the total inverter system loss, the efficiency is 98.9% at half load and 98.5% at full load. The MW inverter system weight is also measured. Without the enclosure and cooling system, which were not optimized in this prototype, the total weight is 55.6 kg, indicating a specific power of 18 kVA/kg.

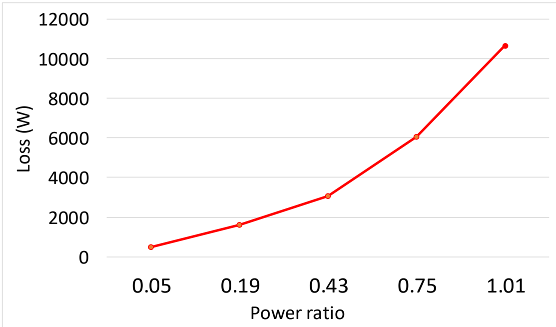


Fig. 21. Tested power stage loss.

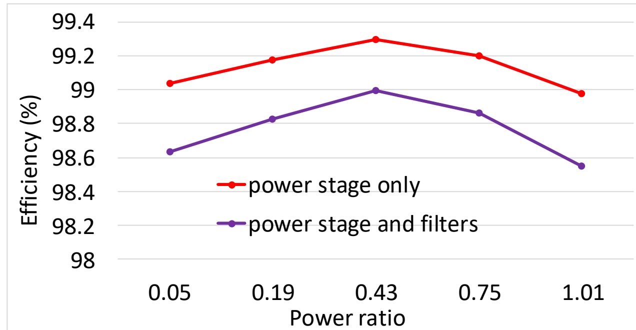


Fig. 22. Inverter efficiency.

It is noted that the inverter prototype does not show an improvement on specific power or efficiency, compared with previously reported MW inverter developed for similar applications using room temperature cooling [12]. One reason is that this MW inverter design assumes the need for inverter AC side to also meet DO-160 EMI standards. Consequently, an AC side EMI filter is required. The assumption of the motor load with high fundamental frequency of 3 kHz and therefore low inductance, exacerbates the situation. To reduce the required AC side filter, especially the DM filter, the carrier frequency of the two inverters are increased to 60 kHz and interleaved, resulting considerable switching loss. The coupled inductors required for interleaving also contributes to appreciably higher weight and loss. In fact, the AC side filter, together with the coupled inductors, contributes about 2/3 of the total inverter system weight. If the AC side has no EMI requirements and only dv/dt filter is needed, the filter weight can be reduced and switching frequency can also be reduced for loss reduction. In this case, the 1 MW inverter system efficiency and specific power can be considerably higher.

V. Conclusion

This paper presents the cooling strategy, hardware and integration, and testing results of a cryogenically-cooled MW inverter system for electric aircraft propulsion system. The dual gaseous and liquid nitrogen cooling strategy is adopted to accommodate the requirements of power stage and EMI filters. The 1 MW inverter hardware and cryogenic temperature testing platform are built. With cryogenic cooling, the inverter system is successfully tested at full load and shows good current sharing capability between the two 500 kW inverters. The 1 MW inverter achieves 18 kVA/kg specific power. At full load, the efficiency of power stage is 99% and the efficiency for both power stage and EMI filter is 98.5%. The developed technology and testing results show that cryogenically-cooled inverter provides a promising solution to achieve high power density and efficiency for future aircraft propulsion applications.

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