2023 IEEE Energy Conversion Congress and Exposition (ECCE) | 979-8-3503-1644-5/23/$31.00 ©2023 IEEE | DOI: 10.1109/ECCE53617.2023.10362337

Module Development of a High-Power-Density High-Efficiency Cryogenic Solid State Circuit Breaker for Electrified Aircraft Propulsion

Shimul K. Dam
CURENT
The University of Tennessee
Knoxville, USA
sdam@utk.edu

Ching-Hsiang Yang
CURENT
The University of Tennessee
Knoxville, USA
cyang30@vols.utk.edu

Zhou Dong
ABB US Research Center
ABB. Inc
Raleigh, USA
zhou.dong@us.abb.com

Dehao Qin
Clemson University
North Charleston, USA
dehaoq@g.clemson.edu

Ruirui Chen
CURENT
The University of Tennessee
Knoxville, USA
rchen14@vols.utk.edu

Fred Wang
CURENT
The University of Tennessee,
Knoxville, USA and
Oak Ridge National Laboratory,
Oak Ridge, USA
fred.wang@utk.edu

Hua Bai
CURENT
The University of Tennessee
Knoxville, USA
hbai2@utk.edu

Zheyu Zhang
Rensselaer Polytechnic Institute
Troy, NY, USA
zhangz49@rpi.edu

***Abstract*— Solid state circuit breaker (SSCB) with high efficiency and high gravimetric power density is required for Electrified Aircraft Propulsion (EAP). A cryogenically cooled GaN device based SSCB module is developed for EAP system. The SSCB module is suitable for medium voltage direct current (MVDC) applications and is designed with low-weight modular cold plates. Each module is rated for 750V, 100A and achieves a power density of 329 kW/kg. The design of the SSCB module structure, thermal design, and insulation design are discussed. Experimental results of interrupting an over-current fault of ~10x of the rated current by the SSCB module is provided to validate its operation at cryogenic temperature.**

Keywords—solid state circuit breaker, cryogenic cooling, aircraft propulsion, high power density, high efficiency.

I. INTRODUCTION

A fast solid state circuit breaker (SSCB) is essential for Electrified Aircraft Propulsion (EAP) system where line impedances are lower, and the system is dominated by power converters with low surge capability [1]. The SSCB in this application should also have high efficiency and high gravimetric power density. Significant efforts are put forward to develop such SSCB using wide bandgap (WBG) power semiconductor devices [2], which offers better performances compared to their Si counterparts with similar ratings. However, due to lack of availability of WBG devices with higher current ratings, several devices need to be paralleled to achieve high efficiency. On the other hand, use of many parallel devices reduces power density and increases SSCB cost significantly.

The efficiency and power density both can be improved using cryogenic coolant available in EAP system that uses liquid Hydrogen as fuel or utilize high temperature superconducting (HTS) machines for propulsion. Studies of characteristics of semi-conductor devices in literature [3], [4] has revealed that their conduction loss can be reduced at low temperatures. This effect is found to be most pronounced in GaN devices, which show monotonic decrease of on-state resistance Rds(on) with reduction of temperature. The Rds(on) for some GaN devices can be reduced as much as five times at Liquid Nitrogen (LN2) temperature [3], [4]. Thus, the efficiency target can be met with using lower number of paralleled devices in case of cryogenically cooled SSCB.

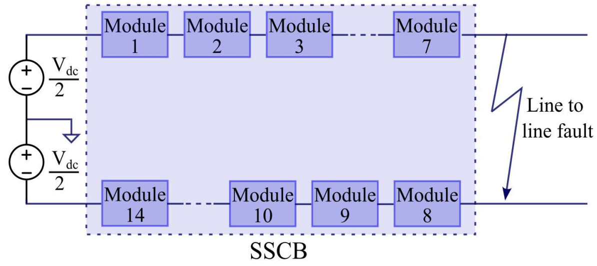


Fig. 1. SSCB in a bipolar dc distribution system under line to line fault condition.

Cryogenic cooling has been demonstrated to improve efficiency of the Si-based 24V 85A SSCB [5] and HTS conductor for current limiting [5], [6]. However, HTS conductors can take 0.5-1 ms to respond [6] and the use of inductors and capacitors can reduce power density of the SSCB in [6]. Also, the Si device show poor performance at very low temperature due to carrier freeze-out, unlike the GaN devices [3]. Apart from this work, this advantage of cryogenically cooled SSCB is hardly exploited in existing literature.

The future EAP systems are expected to use medium voltages (MV) at MW power levels [7]. So, this work presents the development of a high gravimetric power density SSCB based on GaN and LN2 cooling for a bi-polar 10 kV MVDC distribution system. In case of a line to line fault, the SSCB has to block up to 12 kV, considering 20% over-voltage. As the highest voltage rating of available high-power GaN devices is limited to only 650V, the proposed SSCB embraces modular electrical and thermal design. The designed SSCB, capable of blocking 12 kV, has 14 modules as shown in Fig. 1, where each module has two sets of paralleled GaN dies in series and is rated for 750V/100A. The module is also capable of interrupting up to 1 kA fault current. High power TVS diodes are used for energy absorption and reliable voltage balancing [8] among the modules. The modules of the SSCB are divided into two equal groups and placed on the positive

---

This work was primarily supported by ARPA-e, DOE, USA

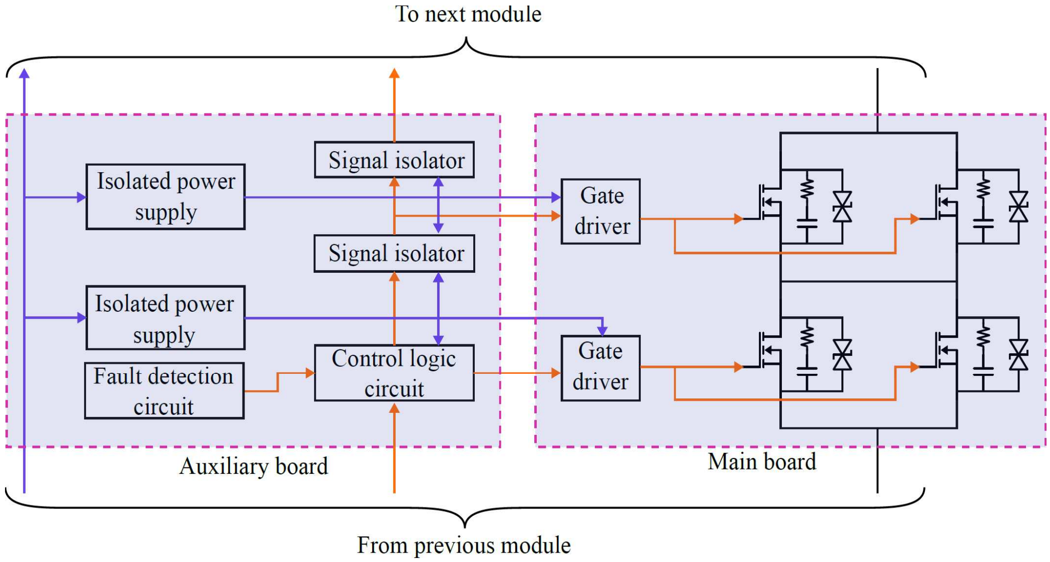


Fig. 2: Architecture of a module of the proposed modular SSCB.

and negative poles of the bipolar MVDC system. This symmetrical placement of modules of the SSCB reduces the module-cold plate and module-encloser insulation requirement from 12 kV to 6 kV, helping to achieve higher power density at lower cost.

The paper is organized as follows, the design of a SSCB module is discussed in Section II, the mechanical and insulation design are discussed in Section III and IV respectively, and the experimental results are presented in Section V, followed by the conclusion.

II. SSCB MODULE DESIGN

The SSCB module has four 650V/150A GaN dies as switching devices. Each GaN die is paralleled with a R-C snubber and a TVS diode, which absorbs the fault energy and extinguishes the fault current quickly. The module is designed to carry 100A current with over 99% efficiency and to interrupt maximum 1 kA fault current at cryogenic temperature (<-153^{0}C). The insulation of the module is designed to withstand up to 6 kV, making this module suitable for 6 kV unipolar dc or 12 kV bipolar dc distribution system.

Apart from the switching devices, each module has other important electrical components and circuits such as gate drivers, signal isolators, control logic circuits, fault detection circuit, and isolated power supplies. To achieve a compact design, the module components are placed on two separate boards: the main board and the auxiliary board. The main board contains the GaN dies, snubber circuit, TVS diode, and the gate driver. The auxiliary board contains all other components. This structure of the module is shown in Fig. 2. The auxiliary board detects faults, receives control commands from the controller, and communicates with other modules.

While lower temperature is more beneficial for efficiency improvement due to monotonic reduction in Rds(on) of GaN device, all other components of the SSCB module do not have any advantage at low temperature. In fact, these components are usually rated for temperatures greater than -40^{0}C and need to be characterized at cryogenic temperature to ensure that the performance of the selected components do not deteriorate significantly at the intended operating temperature.

The designed SSCB module uses LN2 for cooling, which has a temperature of -196^{0}C. However, due to power loss in dies and heat leakage from external environment, the module is estimated to operate around -180^{0}C. So, the components selected for this work have been characterized up to -180^{0}C [9].

III. MECHANICAL STRUCTURE OF THE MODULE

The mechanical structure of the module and cold plate assembly is shown in Fig. 3. Dies are attached to the bottom side of the PCB. The substrate surfaces of dies are soldered on the direct bonded copper (DBC), which is then attached to the cold plate using cryogenic thermal grease. Since the weight of the cold plate is a significant part of the module weight, the top and bottom sides of the cold plate are utilized for cooling purpose. In this way, one cold plate is shared by two SSCB modules and total cold plate weight is halved.

The mechanical structure of one cold plate and two modules is explained in Fig. 3. In this design, the main boards

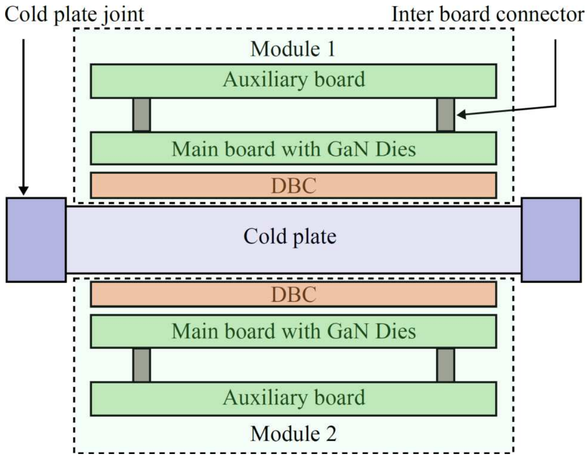


Fig. 3. Mechanical structure of the SSCB module pcb and cold plate assembly.

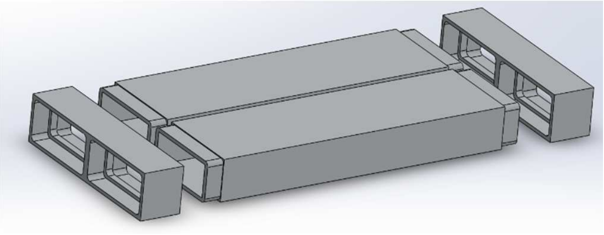


Fig. 4. Modular cold plate and cold plate joint.

with GaN dies are closer to cold plate and the auxiliary boards are away from the cold plate. This arrangement provides thermal insulation to the auxiliary board components, which do not need to be at cryogenic temperature. Inter-board signal connectors are used to send the signals from auxiliary board to main board and to receive the measurement signals. The main and auxiliary board are mechanically supported by nylon spacers and screws. For multiple series modules, a thin copper plate is soldered between the main PCB of two adjacent modules. Spacer length between auxiliary and main board is 20 mm to provide enough clearance for main board components from the auxiliary board PCB. Higher spacing between two boards is better for thermal isolation but leads to less compact design and increased enclosure size and weight.

The SSCB module is cooled with LN2 using a cold plate. As LN2 is an excellent heat conductor, the cold plate does not need large surface area. The required cold plate surface area is determined by the die surface area and die locations. The cold plate is one of the main contributors of total module weight. So, the cold plate is carefully designed to have low weight while having modular structure and sufficient strength to withstand LN2 temperature and pressure. A rectangular aluminum extrusion with low wall thickness of 1.6 mm is used as cold plate. An aluminum joint is designed to connect between two cold plates as shown in Fig. 4. Leakage-free connections between cold plates and the joints are ensured using heat shrink method.

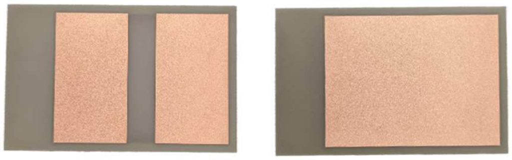
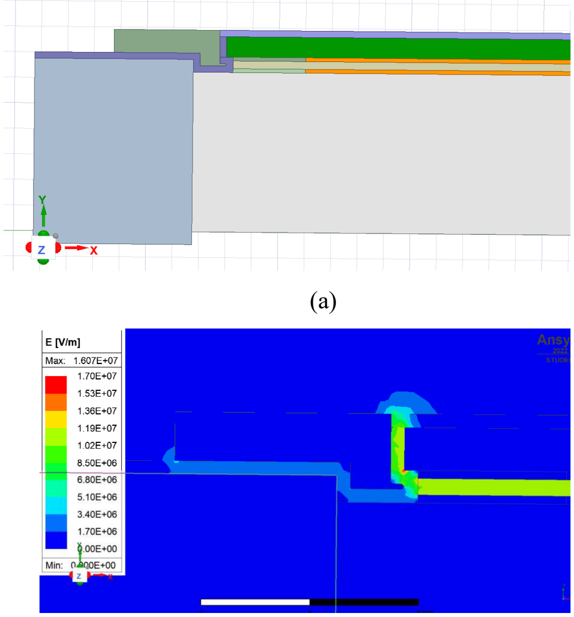


Fig. 5: Top side and bottom side of DBC.

IV. INSULATION DESIGN OF THE MODULE

All the cold plates are electrically connected to each other and to the external cooling system that maintains the LN2 flow in the cold plates. For safe operation, the cold plates and the cooling system are connected to power neutral. On the other hand, when all SSCB is carrying normal system current, the GaN devices of all the modules are turned on and all modules are operating at a voltage of ±Vdc/2 with respect to power neutral, as shown in Fig. 1. Thus, for a 10 kV dc system and 20% over-voltage consideration, each SSCB module is designed to withstand a voltage up to 6 kV with respect to the power neutral. The thermal interface between each module die and the cold plate must withstand this voltage. A DBC is used as the thermal interface to withstand 6 kV, while providing good thermal conductivity. Aluminum Nitride (AlN) is selected as the ceramic substrate due to its high thermal conductivity of 320 W/mK and electrical breakdown strength of 20 kV/mm.



(a)

(b)

Fig. 6. Electrostatic simulation model for cold plate-DBC-PCB assembly and simulated electric field.

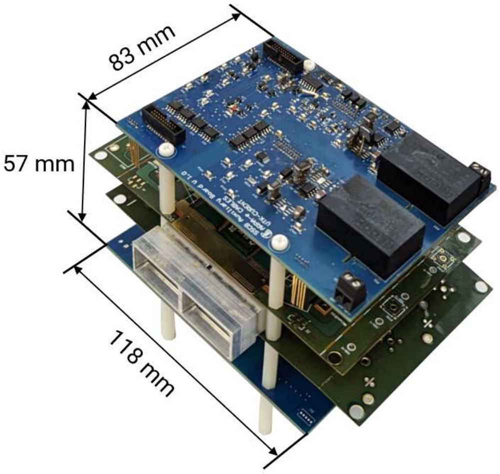
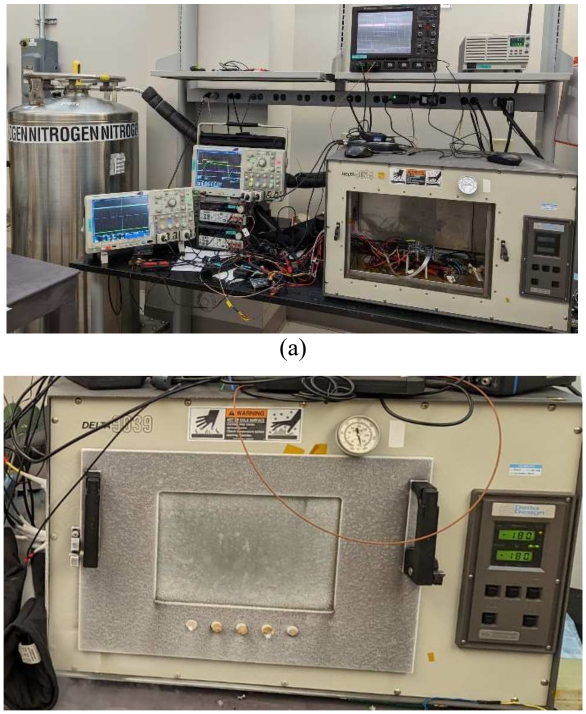


Fig. 7: Developed prototype with two SSCB module and one cold plate.

The top and bottom side of the designed DBC are shown in Fig. 5. The DBC for this SSCB module is designed with 0.6 mm thick AlN which can withstand up to 12 kV. When a voltage of 6 kV is applied between the module PCB and the cold plate, which is connected to power neutral, the highest electric field strength is observed in the area between the edge of the PCB and the exposed cold plate. To prevent any flashover between cold plate and the PCB, the exposed part of the cold plate near the PCB is coated with an epoxy coating material with dielectric strength of 18 kV/mm, as shown in Fig. 10. The thickness of the coating is >0.5 mm, enough to withstand up to 9 kV. However, due to unavoidable sharp edges, the electric field is non-uniform and a higher electric field may be observed. So, the peak electric field need to be



(a)

(b)

Fig. 8: Test setup for testing a SSCB module, (b) sealed thermal chamber at -180^0C.

simulated to ensure that the design is sufficient. The whole module also has a thin transparent coating that protects the components from moisture and condensation.

A 2-D Ansys Maxwell simulation model is developed for the cold plate-DBC-PCB assembly as shown in Fig. 6(a) and electric field is simulated to check the insulation design. Although the module insulation needs to withstand up to 6 kV, the insulation is checked up to 8 kV with enough safety margin. The simulation is performed assuming the worst-case condition with ionized air and PCB filled with copper that has a voltage of 8 kV with respect to cold plate. The simulation result in Fig. 6(b) shows that the highest peak electric field is 16 kV/mm in epoxy and 11.9 kV/mm in ceramic material. Both peak electric fields are within limits of the respective insulation materials.

V. EXPERIMENTAL RESULTS

Prototype SSCB modules rated for 750V, 100A and 10x over-current capability have been assembled with cold plate, as shown in Fig. 7. While the designed module can carry 100A continuously with high efficiency, it also can carry up to 1kA for short duration to allow any normal transient or inrush current without causing any nuisance trip. A test setup is developed to test individual module, as shown in Fig. 8(a) for testing in cryogenic environment. In this test setup, a SSCB module is placed inside a thermal chamber, which uses LN2 to create a low temperature environment. All electrical connections to the SSCB module go through a slot on left wall of the chamber. Then the slot is sealed with fiber glass insulation and the front door of the chamber is closed to create a fully sealed cryogenic test chamber, as shown in Fig. 8(b).

The most challenging test for the SSCB module is to turn-off the GaN devices safely under the 10x over-current condition. This test is performed on the developed prototype in the thermal chamber. The performance of the module is

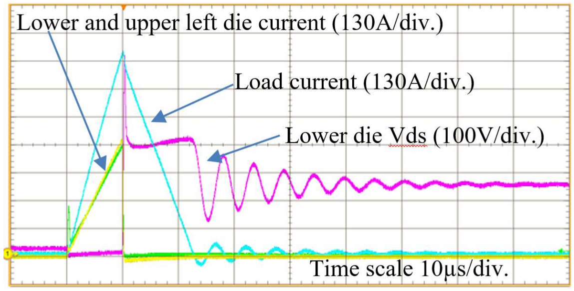


Fig. 9: Voltage and currents during turn-off transition at 940 A fault current at -180^0C.

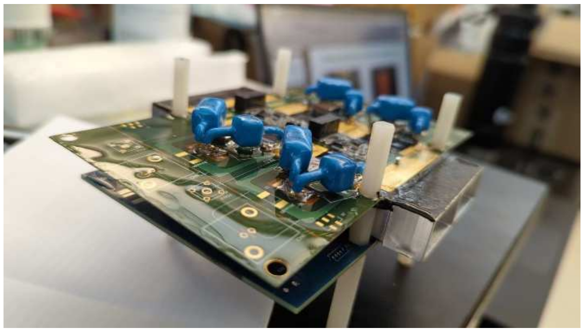
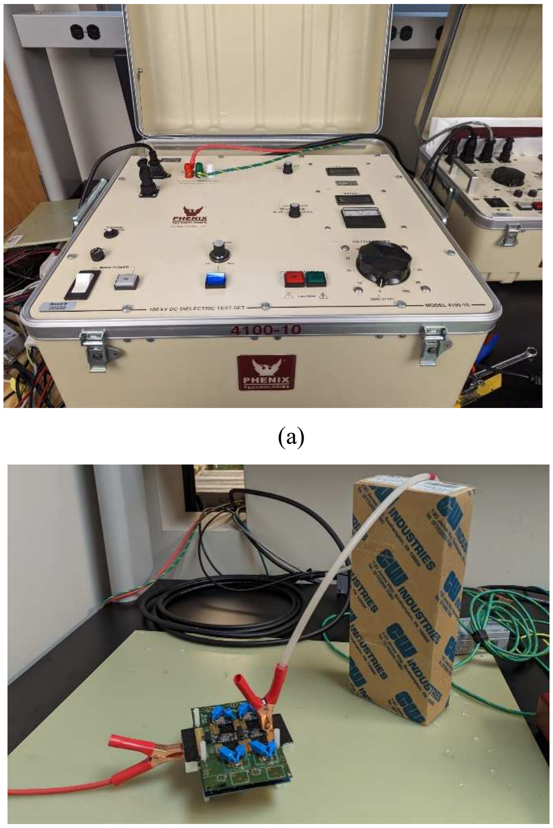


Fig. 10: SSCB module with coating for insulation test.



(a)

(b)

Fig. 11: (a) Insulation test equipment, (b) module under test.

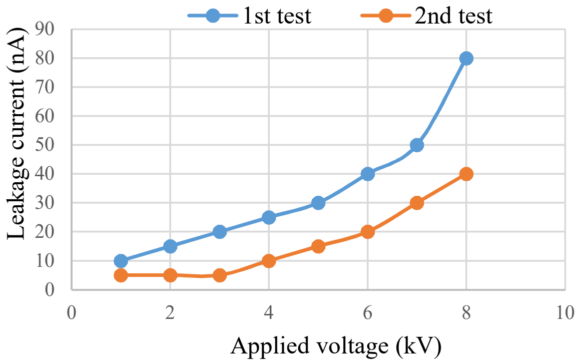


Fig. 12: Observed leakage currents during insulation tests.

evaluated at different temperatures from room temperature down to -180^{0}C, which is the expected die temperature of the LN2 cooled module. The module is tested up to 10x of the rated current, which is 1 kA. The test waveforms in Fig. 9 show a turn-off transition of the SSCB module interrupting a fault current of 940A at -180^{0}C. At the beginning of this test, the SSCB module GaN devices are turned on under a short circuit fault condition and rate of rise of the fault current is limited by a line inductance of 4µH. It can be observed that the total current through SSCB is evenly shared by two parallel GaN devices. When the current reaches the threshold for SSCB tripping, the GaN devices are turned off simultaneously and die currents falls to zero. The voltage across the GaN devices increases until it is clamped by breakdown of the TVS diode. The peak voltage observed across the GaN devices under 1 kA current interruption condition is 716V, which is higher than the voltage rating of the GaN device. However, the datasheet of the selected GaN device sates that the device can withstand 750V for 1 µs [10]. During the turn-off transition of the module test, the drain to source voltage of the GaN device falls back below 650V within 300ns and no failure or loss of performance has been observed due to short-time over voltage. The TVS diode absorbs the stored energy in the line inductance and the fault current is reduced to zero within 13 µs.

A SSCB module with coating on exposed cold plate is tested for its insulation up to 8 kV. As explained earlier, the module needs to withstand 6 kV considering 20% over-voltage and the insulation is tested up to 8 kV to ensure some safety margin for reliability. Since the SSCB is designed for a dc distribution system, a dc hipot tester, as shown in Fig. 11 (a), is used to apply a voltage up to 8 kV on the SSCB PCB with respect to the cold plate. The module connections to the hipot tester leads are shown in Fig. 11(b). The applied voltage is increased from 1 kV in steps of 1 kV. The leakage current is measured after a few minutes of applying each voltage level to allow the leakage current to reach steady state.

The observed leakage currents are plotted in Fig. 12 for two separate tests of the same module. The first test is performed right after the curing of the coating is complete. The second test is performed after three days of the first test. In both the tests, low leakage current is observed, indicating the effectiveness of the insulation design. It can be noted that the leakage currents in the second test is lower compared to the first test. This indicates that the coating material curing improves further with time even after the curing is complete.

The weight of the two modules with one cold plate assembly is 456 g, leading to a power density of 329 kW/kg, higher than any reported power density of SSCBs [2]. A more realistic way to test the module is to use LN2 cooled cold plate instead of a thermal chamber. Currently, the additional required test setup for this test is being developed and the results will be reported in the future.

.

VI. Conclusion

The design of a 750V/100A cryogenic SSCB module using GaN devices is presented in this paper. The module structure design and compact implementation is discussed aiming at high power density. The modular cold plate design for cryogenic cooling and insulation design for 10 kV bipolar MVDC application are discussed. The developed SSCB module prototype has achieved a power density of 329 kW/kg. Experimental results validated fault interruption performance of the designed SSCB module. The insulation design test shows low leakage current when tested at 8kV. Overall, this work demonstrates the feasibility of developing cryogenically cooled GaN based SSCB modules for MVDC application while utilizing the superior characteristics of GaN devices at cryogenic temperatures.

Acknowledgment

This work was primarily supported by ARPA-e, Department of Energy, USA under the award number DE-AR0001467. This work made use of Engineering Research Center Shared Facilities supported by the Engineering Research Center Program of the National Science Foundation and the Department of Energy under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

References

[1] D. Izquierdo, A. Barrado, C. Raga, M. Sanz and A. Lázaro, "Protection devices for aircraft electrical power distribution systems: State of the art," *IEEE Trans. Aerosp. Electron. Syst.,* p. 1538–1550, 2011.

[2] Z. Dong and W. Ren Ren, "Development of High-Power Bidirectional DC," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 5, pp. 5498-5508, 2022.

[3] G. Handong, C. Ruirui, N. Jiahao, Z. Zheyu, T. L. M., W. Fei, B. B. J., C. Daniel and C. B. B., "Review of Power Electronics Components at Cryogenic Temperatures," *IEEE Transactions on Power Electronics,* vol. 35, no. 5, pp. 5144-5156, 2020.

[4] R. Ren, G. Handong, Z. Zheyu, C. Ruirui, N. Jiahao, W. Fred, T. L. M., B. B. J., C. D. J. and C. B. B., "Characterization of 650 V Enhancement-mode GaN HEMT at Cryogenic Temperatures," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, Portland, OR, USA, 2018.

[5] Z. Zheng, X. Chen, X. Xiao, H. Gou, M. Zhang, S. Jiang, B. Shen and L. Fu, "An Ultra-Low-Loss Fault-Current-Limiting Z-Source LVDC Circuit Breaker Using Cryogenic Power Electronics (CPE)," *IEEE Power Electronics Letters,* 2023.

[6] T. Arvin, J. He and K. Waters, "Solid-State DC Circuit Breaker Based on HTS Fault Current Limiter and SiC MOSFET Modules," in *Transportation Electrification Conference and Electric Aircraft Technologies Symposium*, 2022.

[7] R. Jansen, C. Bowman, A. Jankovsky, R. Dyson and J. Felder, "Overview of NASA electrified aircraft propulsion (EAP) research for large subsonic transports," in *53rd AIAA/SAE/ASEE Joint Propuls. Conf.*, 2017.

[8] H. Duan, W. Wang, Z. Shuai, D. He, D. Chen and Z. J. Shen, "A SiC JFETs Modular Cascaded Method With Active Clamp Control Strategy for DC Solid-State Circuit Breaker," *CSEE Journal of Power and Energy Systems,* pp. 1-12, 2022.

[9] D. S. K., Y. Ching-Hsiang, Z. Dong, Q. Dehao, C. Ruirui, W. Fred, B. Hua and Z. Zheyu, "Experimental Evaluation of Cryogenic Performances of Electronic Components for Signal Isolation in Medium Voltage Power Converters," in *2023 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Orlando, FL, USA, 2023.

[10] GaN Systems, "GS-065-150-1-D2, 650V Enhancement Mode GaN Transistor," [Online]. Available: https://gansystems.com/gan-transistors/gs-065-150-1-d2/. [Accessed 18 7 2023].