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Preliminary Design of DC Resistive Superconducting Fault Current Limiter for ASCEND

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***Abstract*—Airbus UpNext has launched an Advanced Superconducting and Cryogenic Experimental powertraiN Demonstrator (ASCEND) project in 2021 to develop a superconducting electric aircraft propulsion system. The demonstrator system power is rated at 500 kW with the DC voltage of 300 V. DC networks can achieve smaller footprint and improved distribution efficiency. However, fault management in DC networks is much more challenging than AC systems because: firstly, there is no natural zero-crossing of the current to isolate the fault; and secondly, the rate of rise of fault currents is often significantly higher due to lower system impedances.**

Resistive superconducting fault current limiter (RSFCL) is a passive device that provides protection without requiring external input, making it inherently reliable. Non-inductive bifilar pancake RSFCL coils supported by G10 former are designed and built based on ASCEND system specification. This paper will present the design of RSFCL using 2G high temperature superconductor tapes for ASCEND demonstrator. A DC fault current testing circuit is built for testing of RSFCL. RSFCL is experimentally tested from 65 K to 77 K in the sub-cooled liquid nitrogen cryostat. The current limitation and recovery time are compared for different operating temperatures. In conclusion, RSFCL using HTS tapes demonstrates effective and fast current limitation within 1ms, which significantly improves the reliability of the system.

***Index Terms*— resistive superconducting fault current limiter (RSFCL), sub-cooled liquid nitrogen, electric aircraft**

INTRODUCTION

AIRBUS UpNext has launched an Advanced Superconducting and Cryogenic Experimental powertraiN Demonstrator (ASCEND) project in 2021 to develop a superconducting electric aircraft propulsion system for net zero target [1]. The adoption of a high-power DC system as the onboard power system in electric aircraft is driven by its adaptable placement options, cost-effective maintenance, and fast transient capability [2]. Due to high power capacity, reliable and safety performance are critical for such dc systems. A RSFCL is considered highly advantageous for limiting current during power system faults. It alleviates the load on circuit breakers when clearing faults, thereby enhancing system protection, and safeguarding electrical equipment. RSFCL is a promising device to be used in DC systems because of its various advantages [3]. Superconductors provide a unique advantage to the SFCL, as it remains lossless during normal operations. However, when the operating current surpasses the superconductor's critical current, it automatically triggers an inherent high-resistance state with rapid response (within milliseconds), all without the need for additional monitoring or control apparatus. Therefore, SFCLs have demonstrated their superiority in safeguarding power systems compared to traditional protective devices. Many RSFCL structures have been proposed and studied, mainly divided into the straight-line type [4], pancake type [5-7] and solenoid type [8-9]. For aircraft applications, the performance of RSFCL in different coolants such as liquid nitrogen (LN_2) and gaseous helium (GHe) has been studied in [10]. Different protection systems for all-electric aircraft were investigated in [11]. One promising technique is cryogenic dc breaker integrated with superconducting fault current limiter [12-14].

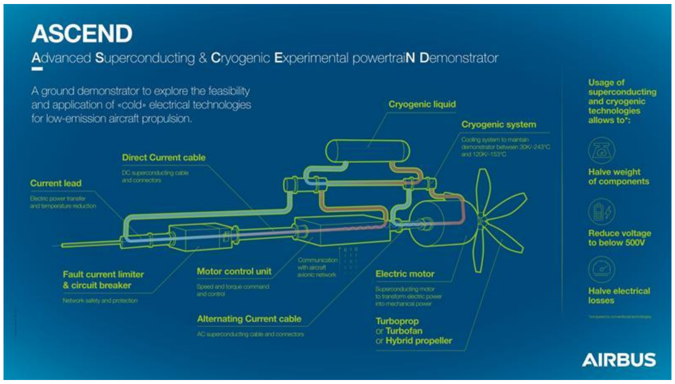

Fig. 1. Airbus ASCEND demonstrator [1].

The ASCEND demonstrator system power is rated at 500 kW with the DC voltage of 300 V. The operating current is 1700 A, and the maximum fault current is required to limit below 6800 A. To design the SFCL for ASCEND demonstrator properly, it is important to investigate the characteristics of SFCL at different temperatures. In this paper, a non-inductive bifilar pancake SFCL coil is designed and experimentally tested from 65 K to 77 K in the sub-cooled liquid nitrogen cryostat. The current limitation and recovery time are compared for different operating temperatures.

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The remaining of this paper is organized as follows. In Section II, experiment set-up is introduced. In Section III, the comparison between the fault current with and without RSFCL is analyzed at different operating temperatures. Finally, conclusions are presented in Section IV.

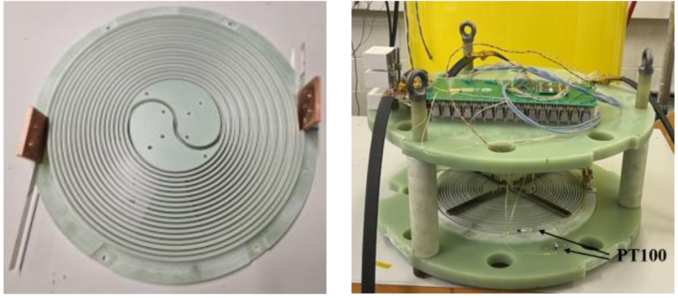


Fig. 2. SFCL pancake coil prototype(left) and test sample holder with SFCL (right).

Fig. 3. Cryostat.

II. EXPERIMENT SET-UP

A. SFCL design

A non-inductive bifilar pancake SFCL coil supported by G10 former is designed and built as depicted in Fig. 2. The high-temperature superconductor (HTS) material used to fabricate the SFCL is the commercial coated conductor tape manufactured by Shanghai Superconductor Technology Co., Ltd. This tape boasts an average width of 12 mm and an average thickness of 0.25 mm. The self-field critical current of this tape is approximately 510 A at a temperature of 77 K. The room temperature resistance of this tape is 100 mΩ/m. The resistive-type SFCL is wounded in a non-inductive configuration with a coil consisting of 20 turns. The diameter of former is determined as 400 mm. Typically, the dielectric strength is 50 V/m, but for conservative design, we consider 30 V/m. With this parameter, the required length of tape is calculated as 300/30 = 10 m. Therefore, the distance between two adjacent turns is 8 mm. This design enhances heat dissipation of SFCL. Approximately 11.6 meters of HTS tape were used in total. Two copper connectors are symmetrically placed along the outermost edge of the coil, firmly affixed to the G10 former. The ends of the SFCL are soldered to these copper connectors, while two voltage taps are soldered to the SFCL. Table I shows the detailed specifications of the SFCL.

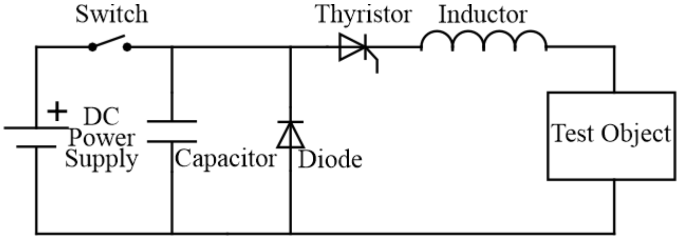


Fig. 4. Schematic diagram of DC fault current test circuit.

TABLE I
SFCL SPECIFICATIONS

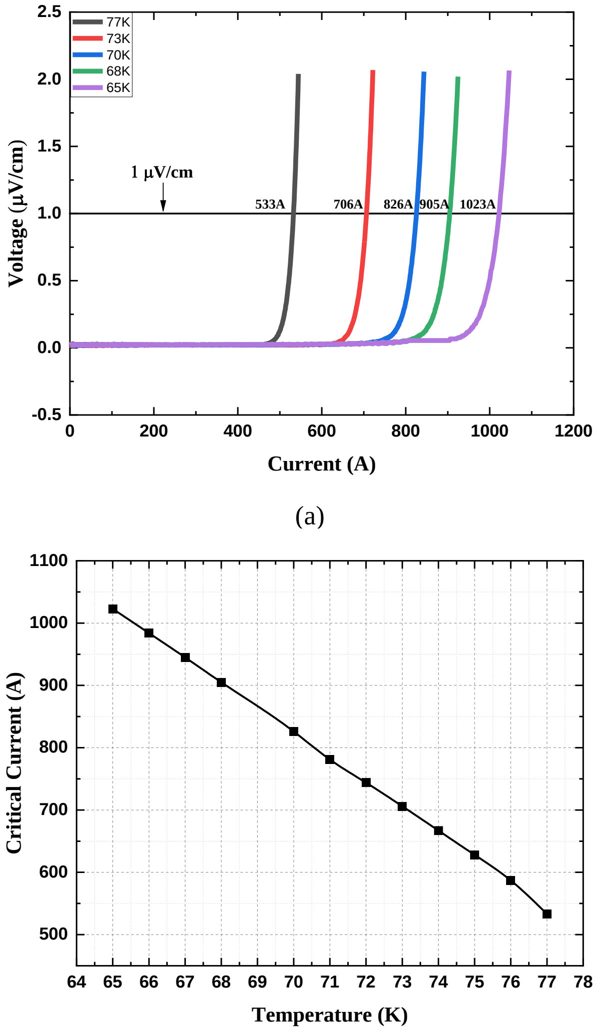
Parameter	Value
Tape	ST-12-L
Lamination material	Stainless steel
Tape width	12 mm
Tape thickness	0.25 mm
Tape Resistance @ RT	100 mΩ/m
Tape Critical Current @ 77K	510 A
Tape length	11.6 m
Number of turns	20
Diameter of former	400 mm

B. Cryostat

Fig. 3 shows the cryostat to investigate the performance of SFCL from 65 K to 77 K. The cold head is AL600 manufactured by CRYOMECH, which provides 600 W cooling power at 80 K. The cooling power at 65 K and 77 K is 470 W and 573 W, respectively. A resistive heater is mounted on the cold head, and PID control is implemented to achieve closed loop temperature control. Several PT100 temperature sensors are positioned at different locations inside the cryostat. Some of them are placed directly on the SFCL to monitor its temperature, as illustrated in Fig. 2.

C. Testing circuit

Fig. 4 illustrates the schematic diagram of the SFCL setup within a DC fault test rig. The test rig utilizes an inductor-capacitor resonant circuit to generate short-circuit fault currents within electric aircraft DC network. This circuit features a capacitance of 12 mF, symbolizing the DC bus capacitor in the electric aircraft. When the switch is closed, this capacitor can be charged using a direct current power source. Inductor is designed to represent the system fault condition, which is 30 μH with air-core. The SFCL coil is connected in series with the inductor. Following the capacitor's charging to the desired level through a DC power supply, the switch is deactivated. Upon activation of the thyristor, the fault current passes through the SFCL coil. A



(a)

(b)

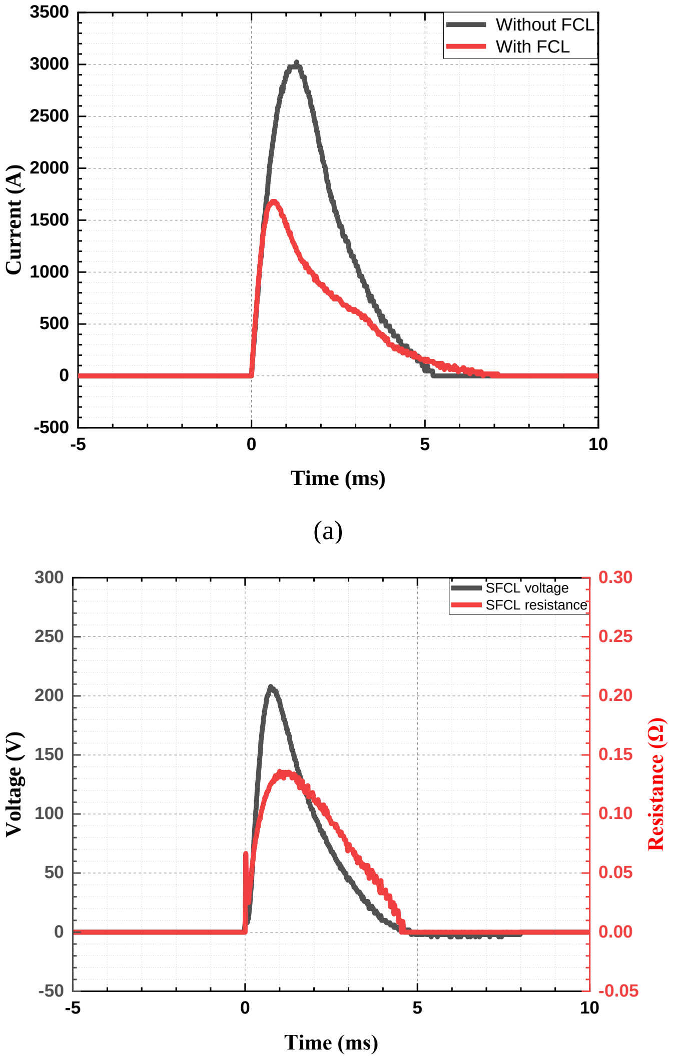
Fig. 5. Measured critical current values at different temperatures.

diode, symbolizing the freewheeling diodes on the converter side, serves as a protective measure for the capacitor.

III. Experimental Results and Discussion

A. Critical Current

Fig. 5 (a) shows the measured E-I curves of the SFCL at different temperatures. The critical current is obtained by using 1 μV/cm criterion. At 77 K, the critical current of the SFCL is 533 A, which is a little bit higher than short straight tape itself. This is because self-field is canceled by bifilar structure. The critical current is 706 A at 73K, 826 A at 70 K, 905 A at 68 K, and 1023 A at 65K, respectively. The critical current increases with decreasing temperature, showing a linear relationship in Fig. 5 (b). According to this figure, we can design the SFCL as well as operating temperature for ASCEND demonstrator. For example, we can design two tapes in parallel operating at 65 K for normal operation current, or three tapes in parallel operating at 68 K.



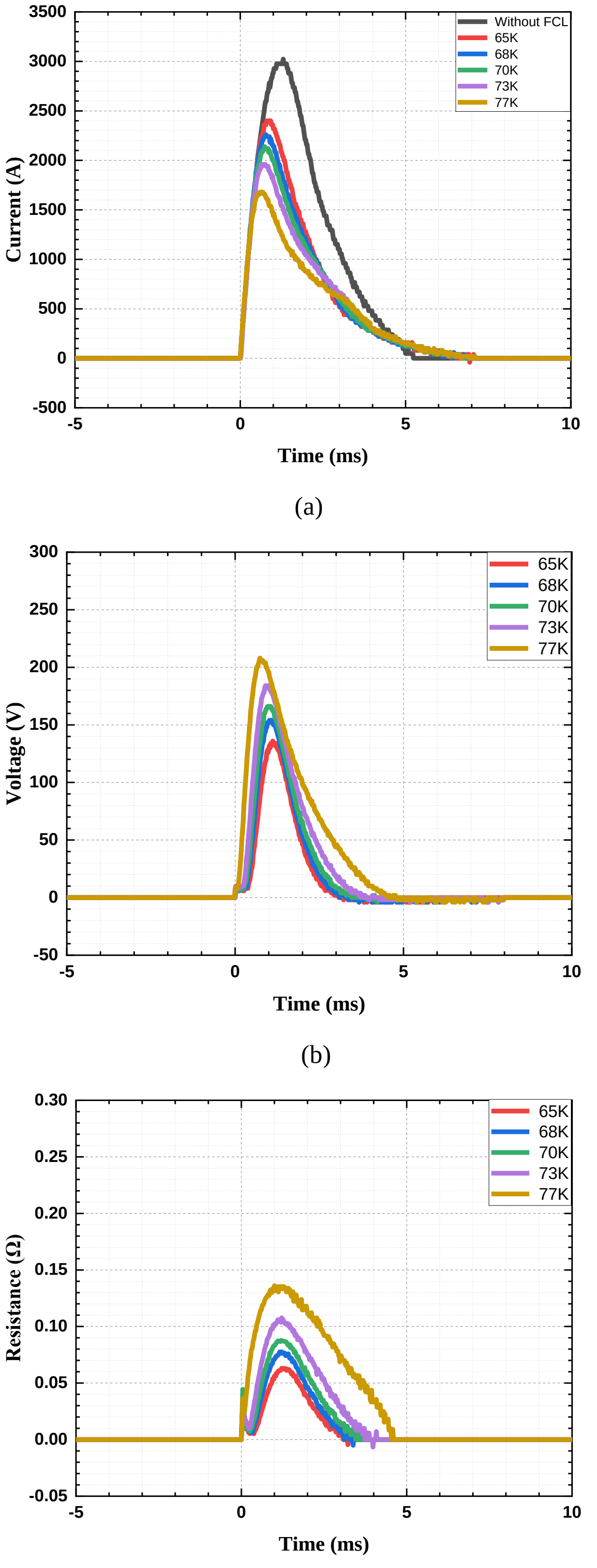
(a)

(b)

Fig. 6. (a) Current limitation at 77 K. (b) Voltage across the SFCL and resistance of the SFCL at 77 K

B. SFCL current limitation at 77 K

According to ASCEND specifications, the capacitor voltage is charged to 300 V to do current limitation tests. As shown in Fig. 6 (a), in the absence of the SFCL, the fault current surges sharply to its peak value of 3024 A within 1.3 ms. The fault current does not last for long time because of limitation of value of the inductor and capacitor in the test circuit. Quench experiments are carried out in a liquid nitrogen bath. The SFCL effectively restrained the peak fault current to 1680 A, which is about 55% of the prospective fault current. Concurrently, the voltage across the SFCL reached 208 V, indicating that the majority of the voltage drop occurred within the SFCL as shown in Fig. 6 (b).



(c)

Fig. 7. (a) Current limitation at different temperatures. (b) Voltage across the SFCL at different temperatures. (c) Resistance of the SFCL at different temperatures.

As the fault duration prolonged, the resistance of the SFCL exhibited a significant rise due to quenching behaviour. This was accompanied by a substantial release of heat energy, which in turn led to further temperature escalation. This positive feedback loop ultimately resulted in a continuous increase in SFCL resistance, culminating in a declining current trend During this period, the peak quench resistance of the SFCL is about 0.14 Ω.

C. SFCL current limitation at different temperatures

The SFCL is tested at different temperatures from 65 K – 77 K in the cryostat as shown in Fig. 2. The test circuit is the same as last section, which the capacitor is pre-charged at 300 V. Fig. 7(a) shows the current limitation performances at different temperatures. With the same prospective fault current, the limited current increases with the decreasing temperature. Compared to 1680 A at 77 K, the limited current is 2400 A at 65 K, which increases to 80% of prospective fault current. The primary reason for this is that the critical current of the SFCL is nearly double at 65 K compared to its value at 77 K.

Fig. 7 (b) shows the voltage across the SFCL. The peak voltage decreases with the decreasing temperature. Fig. 7 (c) indicates the resistance of the SFCL. After the peak value, the resistance of the SFCL did not instantaneously vanish, but instead gradually decreased to nearly 0 Ω within some time. This clearly illustrates that the recovery time at lower temperatures is shorter compared to that at higher temperatures. The reasons include the heat generated at lower temperature is less as well as the liquid nitrogen can take more heat away at lower temperature.

VI. CONCLUSIONS

We have successfully constructed and conducted experimental tests on a Superconducting Fault Current Limiter (SFCL) prototype under cryogenic conditions. To maintain the prototype at cryogenic temperatures ranging from 65 K to 77 K, a specialized cryogenic cooling system was designed and implemented.

Our investigation focused on assessing the current-limiting capabilities of the SFCL prototype across this temperature range. It was observed that as the temperature decreased, the critical current capacity of the SFCL coil increased. This signifies that under normal operating conditions, the SFCL coil can effectively accommodate higher levels of current.

The SFCL coil exhibited substantial current-limiting capabilities once the fault current surpassed double the critical current threshold. Moreover, as the prospective fault current peak value increased, the effectiveness of the current-limiting feature was further pronounced. This study presents preliminary design results for a single-tape RSFCL at various operating temperatures. The current-limiting performance and current-carrying capacity exhibit variations at different temperatures, providing valuable insights for the design process. In practical applications, careful consideration should be given to selecting the optimal operating temperature to ensure both sufficient current-carrying capacity and enhanced current-limiting performance. Our research underscores the immense potential and practical viability of implementing SFCL technology in cryogenic electric aircraft systems.

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