Performance of the 500 kW Superconducting DC and AC Links of the ASCEND Demonstrator at Airbus

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***Abstract*—In the quest for climate neutrality in the aviation industry by 2050, technology development is one of the main pathways for Airbus. Owing to their high efficiency and current density, use of superconducting DC and AC distribution lines are a potential enabler for fully electric propulsion in a longer range aircraft, in particular in the scenario where liquid hydrogen provides a cold source on board of the aircraft. The ground-based Advanced Superconducting and Cryogenic Experimental power traiN Demonstrator (ASCEND) at Airbus intends to demonstrate the potential and feasibility of a cryogenic and superconducting powertrain as a breakthrough electric propulsion solution on future electric aircraft. A direct current distribution network is used in a generic propulsion system to transfer 500 kW power from the DC supply to an electrical converter, which transforms the energy into an alternating voltage/current to drive the superconducting motor. A relatively low voltage level of 300 V, and a current of 1700 A, is chosen to optimize the safety and installation in a future aircraft by operating at relatively low voltage. The DC link consists of a 10 m long two-pole superconducting Conductor on Round Core (CORC) cable, and demountable current leads, that transfer the power from the room temperature environment to the cryogenically cooled motor control unit. Downstream of this unit a 3-phase AC link operating at 500 Hz delivers power to a superconducting motor. Both the AC and DC links are cooled with a flow of subcooled LN_2. The components of the DC and AC links have been designed, manufactured and recently integrated into the ASCEND test bench in Ottobrunn, Germany. We present the powering of the DC link up to nominal current, as well as commissioning and integration experience.**

***Index Terms*—DC distribution systems, electric aircraft, high-temperature superconductors.**

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I. Introduction

To DECREASE dependency on carbon based fuels, Airbus is exploring multiple technology pathways, one of them the full electrification of aircraft [1]. This development comes with several challenges. Optimizing weight and efficiency is particularly challenging for high power airborne application, especially beyond 5–10 MW. Due to their higher current densities, powertrains operated at cryogenic temperatures and using superconductors have been identified as potential enablers for large fully electric aircraft, thus opening a path to the ambitious goal of net zero [2], [3], [4]. The optimal scenario for such a powertrain would be an architecture where liquid hydrogen fuel is present on board the aircraft, such that the stored fuel can be used as a cold source for the electric propulsion system [5].

In 2021, Airbus announced the launch of a project called Advanced Superconducting and Cryogenic Experimental powertraiN Demonstrator (ASCEND) [6]. The purpose of ASCEND is to demonstrate the potential and feasibility of a cryogenic and superconducting powertrain as an enabler for aircraft electric propulsion technologies. One of the main deliverables of the project is to build a ground demonstrator at the Airbus premises, before the end of 2023. The ground demonstrator consists of a superconducting DC link, a motor control unit, a three-phase AC link and an electric motor, all cryogenically cooled and integrated in a test bench at the Airbus Electric Aircraft Systems Test House in Ottobrunn, Germany. The layout of the powertrain is presented in Fig. 1. The layout of the components of the powertrain in the test station is illustrated in a digital mock up of the assembly (Fig. 2). The objective of the project is to demonstrate the possibility to significantly reduce the weight and losses of electrical components of the powertrain and to reduce the voltage and the volume compared to conventional systems thanks to the high current density and low losses of superconducting and cryogenic components. Operating voltages at below 500 V is favorable to manage arcing and partial discharge, which become especially challenging at high altitude. By designing a powertrain working at higher current, and reducing the voltage, the insulation thickness can also be reduced. In this paper, we present the results of powering the 10 m long DC link for the first time.

II. Design and Assembly of the DC Bus

The design parameters of the DC link are shown in Table I. The DC link consists of two 10 m long CORC cables (one for each pole) [7], [8], inserted in a double walled corrugated vacuum insulated Nexans Cryoflex cryostat with 21 mm inner diameter and outer diameter of 44 mm. The cryostat is terminated with

TABLE I
DESIGN PARAMETERS OF THE DC BUS

	VALUE	UNIT
Conductor layout	CORC® with 24 Superpower SC4050 tapes on aluminum core	
DC cable design temperature	67-70	K
Critical current at 77 K	3000	A
Nominal current	1700	A
Nominal voltage	300	V
Current lead heat load (Per lead)	100	W
Maximum short circuit current	6800	A
Short circuit duration	10	ms
Withstand voltage	2000	V
Length of DC bus	10	m

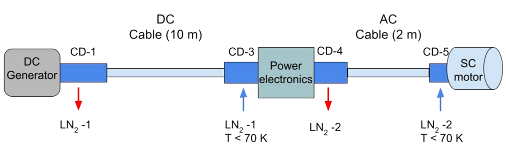

Fig. 1. Layout of ASCEND demonstrator.

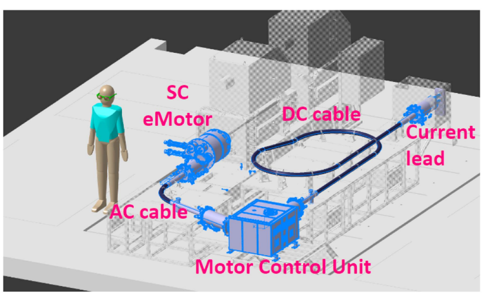

Fig. 2. 3D model of the powertrain, as assembled in the test bench.

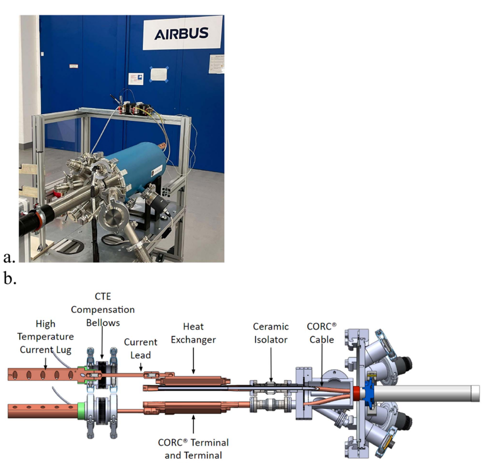

Fig. 3. (a) The assembled connecting device housing the main current leads with visible cryostat connection at the front and current lugs at the end. (b) Internal view of the connecting device.

standard Johnston couplings. The CORC cables are cooled by subcooled flowing liquid nitrogen in a closed loop cooling circuit. The DC bus is terminated by so called connecting devices, see Fig. 3(a), that couple to the cryostat. The internal design is shown in Fig. 3(b). The connecting devices house current leads in vacuum (10^{-5} mbar), optimized according to McFee [9]. The length of the copper current leads is 16.8 cm and the diameter is 1.0 cm. On the power supply side the current leads are optimized for a connection to ambient temperature, and on the motor control unit side they are optimized to the operating temperature of the motor control unit (100 K). Copper heat exchangers cooled with LN_2 flowing at a rate of 130 g/s are designed to extract 200 W of heat losses per lead, which is approximately twice the expected heat load at nominal current and the nominal operating temperature. The dimensioning of current leads and heat exchangers have been performed using finite element modeling. A more detailed description of the design of the connecting devices is given in [10].

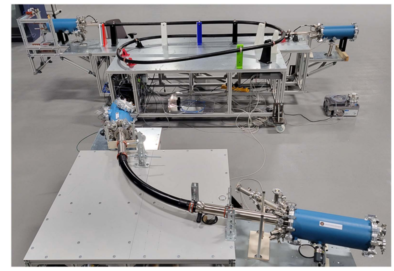

Fig. 4. Assembled 10 m long DC bus (in the background) and 2 m AC bus (at the front table).

TABLE II
ACHIEVED PERFORMANCE AND FIGURE OF MERITS OF THE DC BUS

	VALUE	UNIT
Cryostat outer diameter	44	mm
Cryostat bending diameter	35	cm
CORC® cable outer diameter (insulated and shielded)	7	mm
CORC® cable weight (2 poles)	0.286	kg/m
Cryostat unit weight	0.8	kg/m
Cryostat terminations	Johnston couplings	
Coolant weight	0.2	kg/m
Total weight/meter	1.3	kg/m

The DC link is designed for steady state operation. The main objective is to deliver 500 kW to the motor control unit followed by the AC link and the electric motor that will be installed at the end of 2023. Keeping in mind the intended application in an aircraft, other main design drivers are component's weight, size, mechanical flexibility and electrical efficiency. In addition, simplicity and maintainability is favored.

Fig. 4 shows the assembled DC and AC buses. The achieved figure of merits of the DC link are shown in Table II. The unit weight of the cable and cryostat assembly is 1.3 kg/m including the LN_2 in which the two cable poles are immersed. This unit weight is even better than the initial ASCEND specifications (2 kg/m). However, one must also consider the significant weight added by the terminations, in this case Johnston couplings, instrumentation ports, the enclosure containing the current leads, heat exchangers and cooling lines in a vacuum environment. The weight of the 10 meter DC link of ASCEND adds up to 45 kg in total. This figure will significantly be reduced in the next iteration by customizing in particular the components of the enclosure, that in the ASCEND demonstrator are based mainly on off the shelf products.

The AC link consists of three separate CORC cables, one for each phase, inserted in a larger size cryostat in order to ensure enough separation between the three phases to reduce the AC losses [10]. The development of the AC cable and the preliminary tests of the prototypes are presented in a separate publication [11].

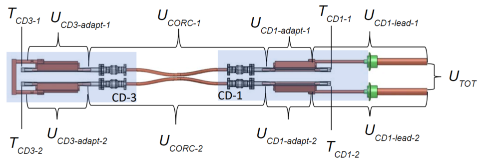

Fig. 5. Overview of voltage wires (labeled U) and temperature sensor (labeled T) location in the DC link setup. The dimensions are not to scale.

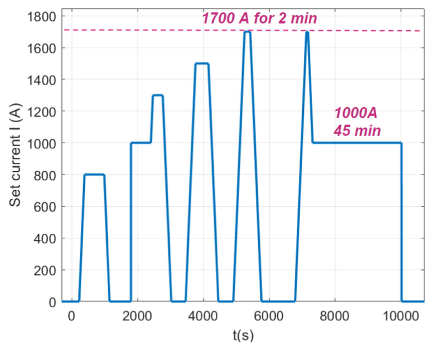

Fig. 6. Powering cycle of the DC link. Current was held at several current levels, and ramped down to zero in between.

III. Performance of the DC Bus

For this first integrated test, the full 10 meter DC link was assembled, cooled down and powered stand alone. The two current leads at the end of the cables on the motor control unit side were shorted with a copper bar and the vacuum space was closed off with a flange. No leaks occurred during the three thermal cycles to 80 K of the DC link assembly.

On the power supply side of the DC bus, heaters on the current lugs at room temperature maintained their temperature in the absence of a transport current, thereby preventing the current leads from freezing. The assembly was cooled down with subcooled flowing LN_2 to 76.5 K with a mass flow rate of 100 g/s, which was the lowest achievable temperature and highest possible flow rate in this temporary setup, i.e., almost 10 K higher than the design temperature.

During all the powering tests, which lasted for three days, no icing or condensation was observed on the DC link components.

The instrumentation on the DC bus is shown in Fig. 5. Voltage wires are installed over the 10 m long CORC cables as well as over sections in the connecting devices. The link is quench protected through a circuit breaker that opens if the voltage over any of the cables exceeds 2 mV for a minimum duration of 2 ms. Temperature sensors are installed in the connecting devices.

The aim of the test was to verify the design of the superconducting link by energizing it up to nominal current.

The set current in the link is shown in Fig. 6. The purpose was to operate for a few minutes at each set current level and observe the thermal behavior of the components in the link, in particular on the connecting devices. Between each set current level, the carrying current was ramped down to zero to allow the components under tests to recover to the initial temperature. Temperature and voltages were stable over time for all set currents up to 1000 A. At 1300 A and above, a slow increase in temperature was observed inside the connecting devices. At the nominal current of 1700 A, the temperature in the connecting devices and on the current lugs where the current is injected increased significantly and a 2 K temperature increase was observed in the coolant exiting the component under test.

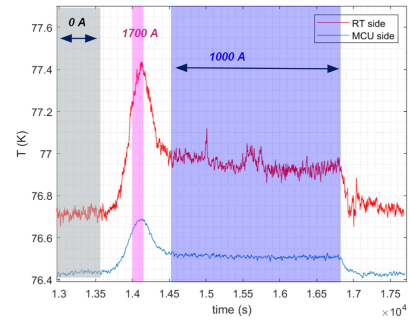

Fig. 7. Temperature plotted as a function of time of the two current leads - one in the connecting device connected to the room-temperature (RT) side (red curve), and the other to the motor control unit (MCU) side (blue curve).

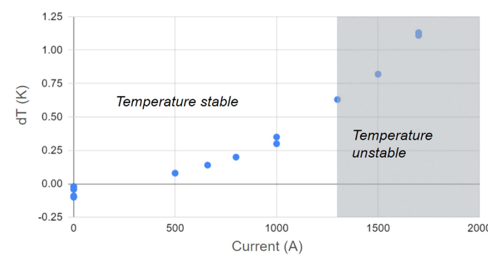

Fig. 8. Temperature rise during the current flattop as a function of the set current in the connecting device to the motor control unit. At carrying current of 1300 A and above, the temperature was not stable, but a slow increase was observed in both connecting devices of the DC link.

Therefore, operating at the nominal current of 1700 A was limited to a maximum of two minutes at a time. It is worth pointing out that the CORC cables were far from quenching, as the measured voltage over the 10 meter cables were less than 100 µV (i.e., 0.1 µV/cm) at each time of the test.

The system recovered to thermal stability at 1000 A even after the 2 min operation at 1700 A, without the intermediate 0 A ramp. A current of 1000 A was maintained for 45 min with stable temperature. The temperature measurement in both connecting devices of the DC link during the 0 to 1700 to 1000 A current profile is shown in Fig. 7.

The measured temperature of the copper parts inside the connecting devices was 76.5 K on average in the absence of DC current, but increased as current was applied. The temperature increase with respect to the zero current case measured in the connecting device to the motor control unit is shown in Fig. 8.

The thermal behavior at full power will be clarified in coming tests under nominal cooling conditions, i.e., nominal temperature and nominal mass flow rate. Then we will be able to confirm that current leads and heat exchangers are well designed and dimensioned to generate low losses and extract these losses.

IV. Conclusion

A compact and flexible two-pole DC link based on CORC cables has been designed, manufactured and integrated in a test bench at Airbus. The DC link was energized to a nominal current of 1700 A at flowing LN_2 at 76.5 K during two minutes. A current of 1000 A was maintained for 45 minutes. The test time was limited by the cooling system, which couldn't yet be operated at its design power and flow rate. The next step is to assess the performance at nominal temperature (<70 K) and nominal mass flow rate. The design choices are compatible with the flexibility and simplicity of maintenance of the test bench.

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