Design of the Superconducting AC and DC Distribution for the ASCEND Demonstrator at Airbus

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(Invited Paper)

***Abstract*—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 propulsion chain to transfer 500 kW of power from the source to an electrical converter, which transforms the power into an alternating voltage/current to drive a superconducting motor. The working point of 1,700 A and 300 V is chosen for safety and installation reasons by operating at relatively low voltage. The direct current (DC) bus of ASCEND will be formed by a pair of high-temperature superconducting CORC cables inserted into a 10-meter-long narrow cryostat, resulting in a compact and lightweight solution. The 2-meter-long alternating current (AC) bus between the inverter and the electric motor is formed by a three-phase CORC cable. The challenge associated with 500 Hz operation in which a balance between AC loss in the cable and the size and mass of the system needs to be found, will be outlined. The AC and DC buses include several devices that connect the liquid nitrogen cooled power cables with the other system components that, in the case of the room temperature generator, operate at significantly higher temperatures. These devices thus include conduction-cooled current leads that are dimensioned to minimize the heat inleak from the warm to the cold environment. An overview of the design of the AC and DC buses and connecting devices will be provided and some of the design and operational challenges will be outlined.**

***Index Terms*—High-temperature superconductors, DC distribution systems, electric aircraft, resistive superconducting fault current limiters, cryogenics, AC loss.**

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I. Introduction

In ORDER to reach climate neutrality in the aviation industry by 2050, technology development is one of the main pathways for Airbus. Fully electric propulsion in longer range aircraft comes with challenges in which superconducting and cryogenic technologies could be enablers thanks to their high efficiency and high current density.

Superconductors have been used for decades in many different applications, mainly on ground, where a high current density is required. At Airbus, superconductivity was first explored in 2018 through the SuperOx demonstrator in a collaboration with SuperOx in Russia [1], where a high temperature superconducting link was designed and tested at 2 kA in DC and at 1.4 kA_{RMS} at a frequency of 400 Hz in AC in boiling liquid nitrogen at an operating temperature of 77 K.

Given the promising results of the SuperOx demonstrator, in particular the compactness and low loss to power ratio, a superconducting powertrain ground demonstrator was launched at Airbus UpNext in 2021 called Advanced Superconducting and Cryogenic Experimental power train Demonstrator (ASCEND) [2]. With ASCEND, Airbus intends to demonstrate the potential and feasibility of a cryogenic and superconducting powertrain as breakthrough aircraft electric propulsion technologies. In the first stage of the project a ground demonstrator will be built and tested at the Airbus premises in Ottobrunn, Germany, before the end of 2023. 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. The optimal scenario for these technologies is 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. In this paper, the design and preliminary results based on laboratory tests and modelling of the DC and AC distribution of the ASCEND demonstrator are presented.

II. General Overview of the Demonstrator

The general layout of the ASCEND demonstrator is shown in Fig. 1. A DC distribution network is used in a propulsion chain to transfer power from the DC power supply to an electrical inverter

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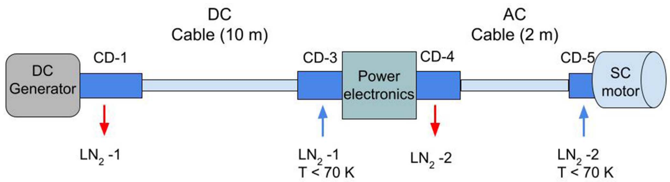

Fig. 1. General layout of the ground demonstrator ASCEND. The ground demonstrator contains a superconducting DC bus, cooled with circulating LN_2, with current leads and fault current limiter, a cryogenically cooled electrical inverter, a LN_2 cooled 3-phase superconducting AC bus, a partially superconducting electric motor and cryogenic cooling systems. The components are connected by so called connecting devices (CD) that transfer the power from one component to another. The function of each connecting device is described in Section III and IV.

TABLE I
DESIGN PARAMETERS OF THE DC BUS

	Unit	Value
Nominal current	1700	A
Maximum short circuit current	6800	A
Nominal voltage	300	V
Maximum transient voltage	650	V
Insulation voltage	2000	V
Cable length	10	m
Number of poles	2	
DC cable temperature	<77	K
Bending radius	0.3	m

that converts the power into an alternating voltage/current to drive the superconducting motor. The functions fulfilled by the DC bus are therefore energy transport but also protection of the network against faults such as a short circuit or arcing to ensure the safety and reliability of the aircraft. The DC bus consists of a 10 m long two-pole superconducting cable in a narrow cryostat. Current leads connect the source at ambient temperature with the superconducting cables in subcooled liquid nitrogen. The working point of 1,700 A and 300 V is chosen to deliver 500 kW at relatively low voltage. Apart from the energy transport from the DC source to the inverter, the DC bus also includes the protection functionality of the network in case of overcurrent events. An integrated solution of a superconducting fault current limiter (SFCL) and a hybrid DC circuit breaker, capable to break several kA within 5 ms, and operating in cryogenic conditions is currently under development for the ASCEND project [3], [4]. Downstream of the motor control unit there is a 2 m long 3-phase superconducting AC bus that powers a partially superconducting electric motor. In ASCEND the superconducting AC and DC buses are cooled with flowing liquid nitrogen subcooled at 65–68 K. The superconducting AC and DC cables connect to current leads at the ambient temperature side and interface with the cryogenically cooled power electronics at around 100 K and the superconducting electric motor at 35 K over demountable connectors. The operating parameters and dimensions are chosen to represent a generic electrical powertrain. In a future application, the architecture may be different.

The objectives of the ASCEND propulsion system are to apply superconducting and cryogenic technologies to (i) demonstrate the feasibility of a fully electric powertrain operating at low voltage (<500 V), (ii) increase the efficiency of a powertrain by 4-5% and (iii) increase the power density to enable new aircraft architectures.

III. DESIGN OF THE DC BUS

A. Superconducting DC Cables

The specifications of the DC bus are summarized in Table I. The nominal operating parameters of the DC bus are a current of 1700 A and voltage of 300 V at a temperature below 77 K. The 2-pole superconducting DC bus consists of two Conductor on Round Core (CORC) cables [5], [6], [7] made by Advanced Conductor Technologies, each consisting of 24 REBCO tapes, wound onto a round aluminium former with a diameter of 5.0 mm. The 4 mm wide REBCO tapes are wound over eight layers. The cable dielectric is formed by winding 10 layers of Kapton tape, 0.025 mm in thickness, with almost 50% overlap. The voltage rating of the cables is at least 2 kV.

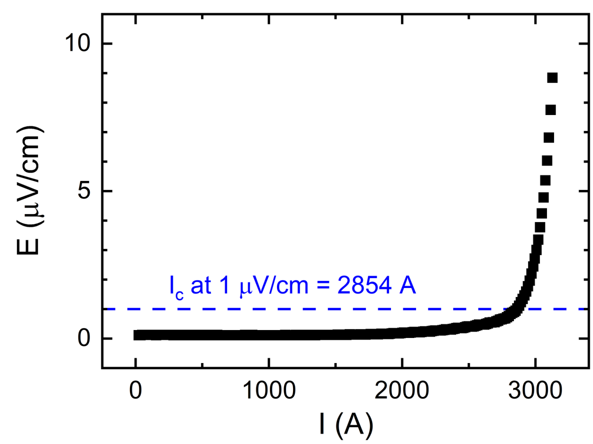

Fig. 2. Voltage per length as a function of current during ramp up at 200 A/s of the CORC DC prototype cable at a temperature of 76 K.

The final diameter of each pole of the DC cable is 7.2 mm, which includes a copper shield layer and final polyester heat shrink tube that keeps the shield layer in place. The cable weight is 0.15 kg/m per pole. Each cable is terminated with a soldered copper termination to ensure a uniform current injection into the tapes. The two poles are twisted around each other and housed in a vacuum insulated Nexans Cryoflex flexible cryostat. The flexibility of the cryostat is 35 cm in radius which is close to the required 30 cm in aircraft installation. The superconducting DC and AC buses are cooled with a common cooling machine, over two parallel cooling loops.

Prototype cables of 0.45 and 0.95 m in length were tested in an open bath of liquid nitrogen, which in Boulder, Colorado boils at 76 K. The electric field, defined as the sample voltage divided by its length, was measured as a function of current during a constant current ramp rate of 200 A/s (Fig. 2), resulting in a critical current (I_c) of 2,854 A. The critical current is

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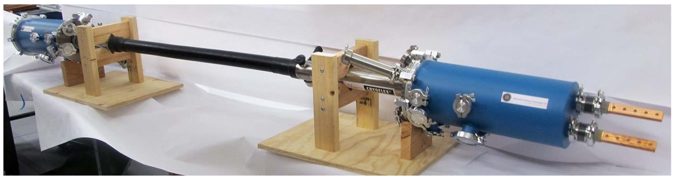

Fig. 3. Overview of connecting device 1 housing the two conduction cooled current leads that connect to the two CORC cables of the DC bus.

defined as the current at a measured electric field of 1 μV/cm. The measurement includes the contact resistance of the cable terminations.

B. Connecting Devices

The interfaces at the ends of the CORC cables are referred to as connecting devices. Connecting device number 1 (Fig. 3) is the interface between the DC supply operating at 295 K and the superconducting DC power cable at 68 K.

The interface contains the two current leads, heat exchangers, vacuum vessel, instrumentation ports, liquid nitrogen lines and a bayonet needed to connect the interface to the cable cryostat. The connecting devices have a voltage rating of 900 V. Connecting device 1 consists of a vacuum enclosure housing a pair of copper current leads, one per DC pole, placed side-by-side within the cryogenic interface that separates the cryogenic environment from the ambient environment. The current lead assembly is housed in a vacuum space to ensure optimal thermal insulation. The vacuum environment is also favorable for voltage breakdown between the cable components. The temperature gradient between 295 K and 68 K occurs entirely over the current leads. The dimensions of the current leads are optimized for the operating current of 1,700 A using the McFee method [8] to minimize the heat load of the current leads into the cryogenic environment through thermal conduction and the Ohmic heating caused by the operating current. The length of the current leads is 20 cm. The theoretical optimal heat load is 80 W per current lead.

The current interface includes the thermal insulation between the low-temperature and ambient environments and provides the interface to the cable cryostat, the cooling lines and feedthroughs for instrumentation. The assembly contains heat exchangers with flowing liquid nitrogen that extract the losses generated in the current leads. The heat exchangers are integrated with current adapters that clamp on to the copper terminations of the CORC cables. The heat exchangers were designed by finite element modelling to ensure sufficient cooling power needed to extract the losses.

An important feature of the interface components is that the connecting devices are practical to demount in case of failure or for maintenance. Therefore, bolted or clamped connections are chosen over soldered or welded joints.

The connection device 3 connects the superconducting DC cable to the power electronics that operate in a gaseous nitrogen environment at a temperature of approximately 100 K. The design of connecting device 3 shares many features with connecting device 1. Like connecting device 1, it contains a pair of current leads with heat exchangers, connectors to the two poles of the CORC DC power cable, the vacuum space between the cryostats housing the DC cable and the power electronics, the connector between the current leads and the power electronics, and all related hardware needed to inject the cryogen. The main difference is that the current leads will be optimized for operation at 100 K at their warm end, instead of 295 K for the DC power supply side. The current leads in connecting device 3 are made of a flexible braiding to allow easier mounting on to the power electronics structure.

The design of the different components in the DC and AC buses are based on subcooled liquid nitrogen at a temperature of 65–70 K. The cooling is provided by a common cooling plant, with two parallel cooling loops for the DC and AC buses with a total cooling capacity of 1 kW. The flowing coolant for the DC bus enters through connecting device 3, continues along to the DC cable cryostat, before flowing through the heat exchangers in connecting device 1, back through the return line in a closed loop.

IV. Fault Current Limiter

A. Design of DC FCL Cable

In an electric powertrain there are scenarios where significant overcurrent can occur. Overcurrent can be caused by short circuits, e.g. following degradation of insulation, or due to mechanical failures in the DC distribution or at equipment level, e.g. in the inverter. The level of fault current depends strongly on the system, but we can assume that fault currents can be on the order of tens of kA. The prospective fault current in the ASCEND demonstrator has been specified as 10 kA. The objective of a fault current limiter is to protect the network and its components from excessive current and to limit the current to a level at which a circuit breaker of reasonable size and efficiency can interrupt, and to keep the Lorentz forces manageable. The fault current limiter of ASCEND should be designed to limit the current to no more than 4 times the operating current which means approximately 6.8 kA for 10 ms.

Apart from transferring DC power from the DC supply to the power electronics, the DC bus contains a fault current limiter that will limit the current in case of overcurrent. Within the ASCEND project a standalone superconducting fault current limiter and a cryogenic hybrid circuit breaker are developed at the University of Bath [3]. The SFCL is based on superconducting tape wound into a bifilar pancake coil. In parallel, another solution to limit the fault current in the network is explored by embedding the fault current limiter functionality within the DC CORC cables themselves [9] by relying on power dissipation within the distribution as the critical current is exceeded and the cable transitions from superconducting to normal state. The advantage of this solution is reduction of weight, volume and complexity as the FCL and the power transfer functions can be merged into one single component, i.e. the DC bus. The drawback may be that the embedded FCL requires a certain minimum cable length, as there is an upper limit to the amplitude of the voltage that can be developed per unit length.

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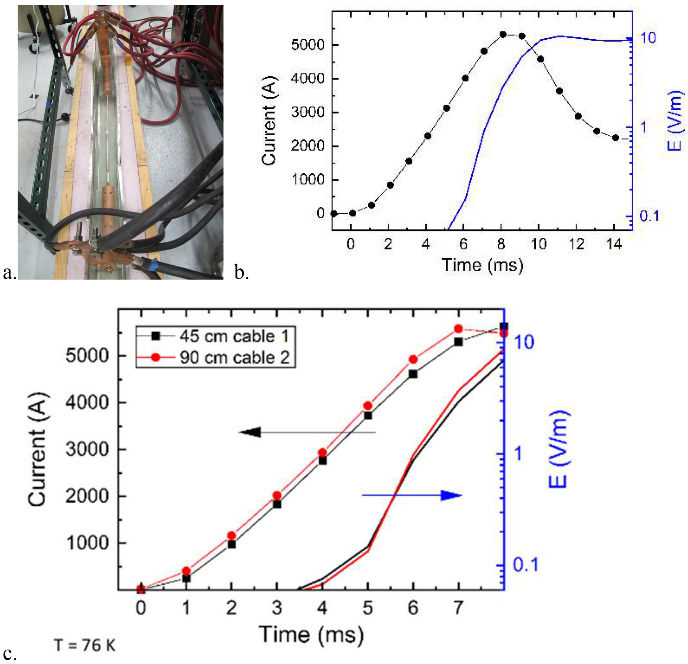

Fig. 4. (a) Setup of powering tests of a 0.96 m long CORC FCL sample. (b) Current and electric field over the CORC cable in the fault current scenario. (c) Current and electric field measured over the two FCL CORC samples of 0.45 m and 0.9 m in fault current tests.

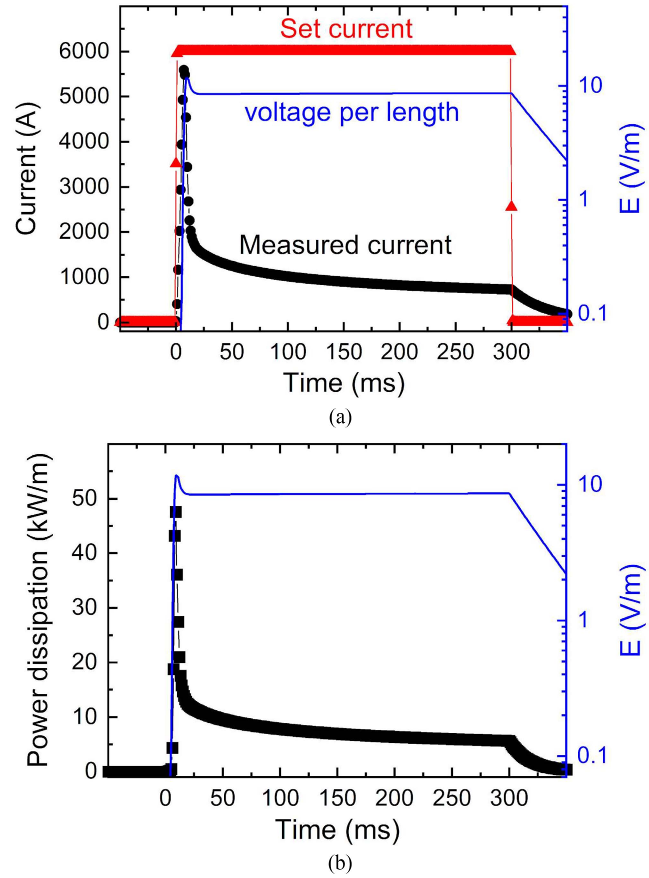

Fig. 5. (a) Measured current in CORC cable sample at a set current of 6 kA for a duration of 300 ms. (b) The dissipated power in the overcurrent test. The electric field reaches 7.5 V/m within 5 ms after the start of the 6 kA fault.

During normal operation the current will be carried in the REBCO layers of the superconducting tapes, and the voltage over the cable will be negligible, due to a small contribution from the cable terminations. However, in an overcurrent scenario the current will instead redistribute into the metal layers of the tapes. When the cable is operated above the critical current, the normal state resistivity will result in a large voltage over the cable, which results in a limited current. In order to dissipate enough power within the DC bus in an overcurrent scenario, an electric field of 10 V/m is targeted over the 10 m long two pole cables. The aluminium core of the CORC cable must be electrically insulated from the current carrying tapes and the cable terminations, since the resistance of the core is too low for sufficient voltage to be developed if current sharing was allowed in the specified overcurrent scenarios. The aluminium former is therefore anodized, and a layer of polyester is used to provide additional insulation of the former from the superconducting tapes.

B. Test Results on CORC FCL Cables

Tests on FCL cable samples were performed to assess the performance in overcurrent scenarios in boiling as well as sub-cooled liquid nitrogen. Due to the voltage limit of 10 V of the power supply, shorter segments of the CORC FCL cable were tested (Fig. 4(a)) to be representative of the voltage over the 10 m two-pole DC bus for the 500 kW demonstrator operating at 300 V. Two samples of different lengths were tested: 0.45 m and 0.90 m between the cable terminations. The critical current of the cables is 2,854 A at 76 K.

In the first tests voltage taps were installed over the cable, and a quench detection system was used to switch off the current 20 ms after detection of a quench. The samples were also equipped with a Cernox temperature sensor under the cable insulation. The current was ramped to above the critical current (max 10 kA) to simulate a fault scenario. An electric field of 10 V/m developed over the cable. As a result the current was limited to 2.2 kA in less than 10 ms. The peak current was 5.3 kA (Fig. 4(b)). The cable transitioned to the normal conducting state and continued to dissipate power even after the current was reduced to the original critical current. The rise in voltage over the cable is due to increased temperature that increases the resistivity of the current-carrying components.

The electric field per unit length is found to be comparable for the two samples of different lengths (Fig. 4(c)) given similar faults, no current sharing with the core occurs and the FCL cable functions as intended.

In the next step the robustness of the 0.9 m long CORC cable to longer fault durations was assessed. The quench detectors were not used, and the current was set to 6 kA during a set duration of 50 and 300 ms (Fig. 5(a)). The voltage rise over the sample limited the peak current to 5.6 kA (1.94 I_c) within 5 ms. Within 10 ms, the current is limited to less than 2 kA. Remarkably, even after a duration of 300 ms of fault operation and over 20

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TABLE II
DESIGN PARAMETERS OF THE AC BUS

	Unit	Value
Nominal current	1800	A_{rms}
Peak current	2350	A
Nominal voltage	183	V_{rms}
Frequency	500	Hz
Insulation voltage	2000	V
Cable length	2	m
Number of phases	3	
AC cable temperature	<77	K

overcurrent tests per sample, no degradation of the CORC cable occurred in terms of critical current or n-value. The measured temperature in these fault tests is 130 K, and the recovery time is approximately 60 s in the case of boiling liquid nitrogen (at 76 K) as the coolant. The cable resistivity at the maximum dissipation of 48 kW/m (Fig. 5(b)) suggests that the actual cable temperature (180 K) could be higher than the measured temperature with the Cernox temperature sensor (130 K). The energy transfer to the coolant depends on the thermal barrier formed by the dielectric. When the heat transfers from the cable to the coolant, it could lead to boiling of liquid nitrogen. The pressure build up in the closed loop cooling system must be taken into account and managed, in particular in a system where the coolant will transition from liquid to gas. In a system cooled by gaseous helium, which will be the case in the next generation of DC bus, the thermal management will be easier due to the absence of a phase transition.

V. DESIGN OF THE AC BUS

The design parameters of the AC bus, which is formed by three CORC cables in parallel, are summarized in Table II. The AC bus will operate at 1,800 A_{rms} and 183 V_{rms} at a frequency of 500 Hz. The design frequency of the powertrain is driven by the design of the electric motor. The weight of the motor decreases with the number of pole pairs by reduction of the magnetic circuit. On the other hand, the operation frequency, and so the AC losses, increases with the number of poles. The choice of the operation frequency is therefore a tradeoff between the weight and the AC losses in the system.

The high current and frequency means that there will be additional effects to predict and manage, compared to operation in DC. First, in the copper parts of the bus, i.e. busbars and current leads, there will be a significant reduction of the skin depth at 500 Hz compared to DC operation. The skin depth decreases with temperature. At 70 K the skin depth in copper is less than 1 mm, compared to around 3 mm at room temperature. Therefore, the skin effect is considered in the design of busbars and current leads that will be made from Litz wires.

Hysteresis loss of the AC bus is calculated using a 2D numerical model based on a cross-section of the cable. Fig. 6 shows the cross-section of the most recent design. The three 24-tape CORC cables are placed in a single flexible cryostat (Nexans Cryoflex 39/66), with 3 mm clearance from the inner wall. Critical current

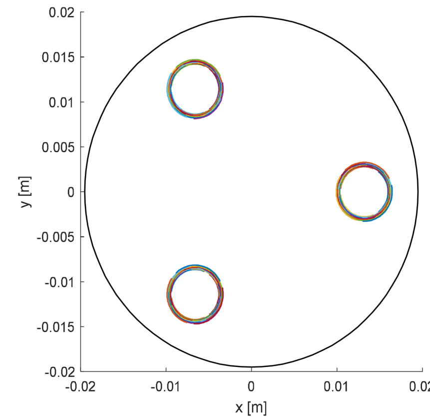

Fig. 6. Cross-section of the baseline design for the AC cable. The black circle represents the 39-mm-diameter inner wall of a Nexans Cryoflex 39/66 cryostat.

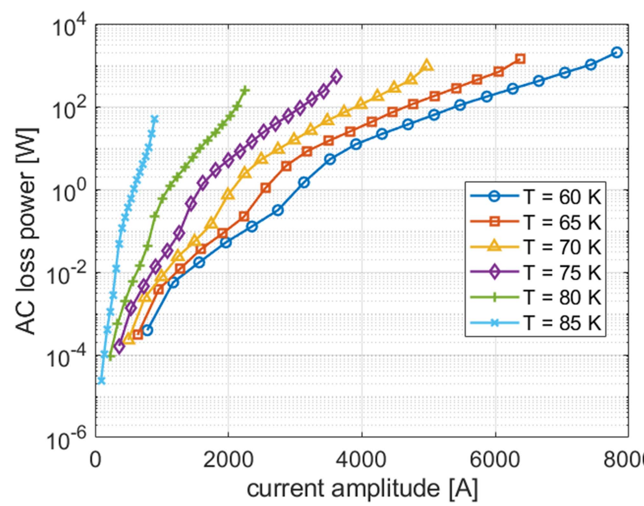

Fig. 7. Calculated hysteresis loss at different temperatures and for different current amplitudes ($f = 500$ Hz).

data, which depends on magnetic field an temperature, were taken from the database of the Robinson Research Institute [10]. The loss was calculated by finite-element modelling in COMSOL (T-A formulation) and a network approach, which both yielded the same values. The 2D COMSOL model, based on the T-A formulation, assumes that the current flows entirely in the superconducting layers and a zero thickness of the tape, based on very large width-to-thickness ratio of the superconducting layer (the width is 4 mm and the thickness is 2 μm) [11]. At an operating frequency of 500 Hz, the losses in a REBCO tape are expected to occur primarily in the superconducting layer [12].

The total hysteresis loss for the 3-phase cables for temperatures in the range 60–85 K are shown in Fig. 7. For each temperature, the calculation is done at 20 amplitudes ranging from 0 A to the respective critical current. A strong dependence on temperature is observed. For example, reducing the temperature from 75 to 60 K at 2,000 A reduces the hysteresis loss by two orders of magnitude.

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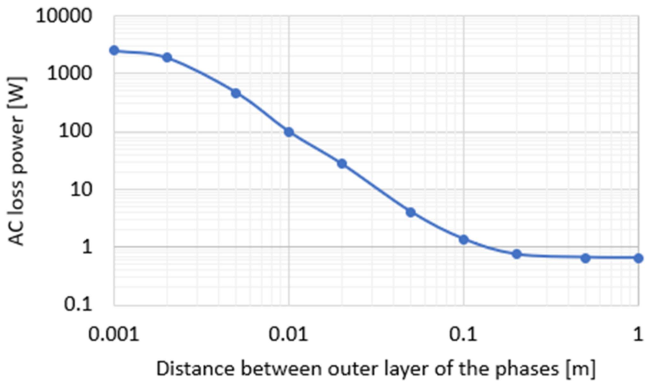

Fig. 8. Calculated hysteresis loss in the two meter long 3-phase superconducting AC cable as a function of the distance between the outer layers of different phases ($I_{\mathrm{peak}} = 2350$ A, $f = 500$ Hz, $T = 77$ K).

Thanks to the concentric layout, the self-field of a CORC cable is parallel to the surface, which results in relatively small associated losses. However, when multiple CORC cables are placed in close proximity, this symmetry is broken and as a result the AC losses are higher. This effect is illustrated in Fig. 8, where the calculated hysteresis loss is plotted against the distance between the individual CORC cables within the 3-phase AC bus. With a low separation between the cables of 1 mm, the loss is as high as 2 kW which exceeds the cooling budget. For this reason, a larger cryostat with 39 mm inner diameter was chosen, which allows increasing the distance between the outer layers of the individual CORC cables to 16 mm. The predicted hysteresis loss for this layout is 40 W at 77 K and can be reduced further by subcooling the liquid nitrogen.

The calculations presented here were done assuming a uniform distribution of current over the strands, which is not guaranteed for time-dependent currents [12]. Also, eddy currents in metallic parts, which can play a role at higher frequencies, were not taken into account. The influence of these mechanisms on AC loss is being investigated at the moment.

VI. Conclusion

The superconducting DC and AC buses have been designed for the 500 kW ASCEND demonstrator currently under development at Airbus. Superconducting CORC cables were chosen for the DC and the AC distribution. The compact, lightweight, and flexible DC cables were designed with fault current limiting functionality to protect equipment from excessive over-currents. Laboratory tests of shorter segments of the FCL CORC cable show promising results, with significant power dissipation for hundreds of milliseconds without any degradation of the superconducting cable.

Due to the high operating current and frequency in the AC bus, significant hysteresis losses in the superconducting tapes in the 3-phase AC bus were predicted by 2D modelling. The hysteresis losses will be limited by allowing sufficient separation between the three phases.

Manufacturing of the DC and AC bus components is currently ongoing at Advanced Conductor Technologies. Integration and testing of the ASCEND demonstrator is scheduled to be completed by the end of 2023.

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