Calculation and Measurement of Transport AC Loss of *Re*BCO CORC Cables for Electric Aircraft

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***Abstract*—This paper investigates transport AC loss in CORC cables for the ground-based demonstrator ASCEND at Airbus, which studies the feasibility of a superconducting powertrain for electric aircraft. The demonstrator includes a three-phase AC link consisting of three parallel cables operating at 500 Hz and 2350 A peak current. The transport AC loss of the three-phase cable is estimated using a 2D model assuming equal current in all tapes. The model predicts an AC loss of 40 W at 77.5 K and 0.4 W at 65 K. A second model is proposed, which computes the current distribution between the tapes in a single cable using mutual inductance matrices for helical tape conductors. This model predicts that, at 500 Hz, the outer two layers of a CORC cable carry a disproportionate fraction of the current. This will lead to additional AC loss if the critical current in the outer layers is exceeded. AC transport loss was measured on single CORC cables. Both models significantly underestimate the measured loss. Also, a frequency-dependent quench current below the DC critical current was observed at 48 Hz and 96 Hz.**

***Index Terms*—AC loss, aircraft, cables, CORC, quench, *Re*BCO.**

I. Introduction

THE Advanced Superconducting and Cryogenic Experimental power train Demonstrator (ASCEND) was developed at Airbus to investigate the feasibility of a superconducting power distribution system for electric aircraft [1]. The demonstrator includes a three-phase AC link of 2 m length that connects the inverter to the electric motor. The AC link comprises three parallel Conductor on Round Core (CORC) cables in a flexible cryostat and carries a maximum current of 2350 A at 500 Hz under nominal conditions. It is inevitable that the AC link produces heat due to various AC loss mechanisms. For stable operation of the link, the AC loss level must remain under control, and the heat needs to be removed by the liquid nitrogen coolant. This requires comprehension of the different loss mechanisms and appropriate thermal design of the cable.

The transport AC loss of CORC, or similar helical tape cables, has already been studied experimentally by other authors, although the samples had only one or two layers [2], [3], [4], [5], [6], [7]. Šouc et al. found transport AC loss to be lower than that of single tapes due to a more parallel orientation of the magnetic field to the tape surface [2]. Solovyov et al. measured transport losses in similar cables to be four times higher than predictions from a two-dimensional model [3]. They suggest irregular gap sizes or a non-uniform current distribution as possible explanations for the discrepancy. Several authors reported eddy currents to appear when an electrically conducting core is used [4], [5], [6], [7].

In this work, we investigate the AC transport loss in eight-layer CORC cables by numerical modelling and preliminary experiments. Section II presents two electromagnetic models, both assuming constant temperature. Model 1 calculates hysteresis loss using a 2D representation of the three-phase AC link (cross-section). It assumes that each tape within a cable carries the same current, which is not necessarily true at higher frequencies. Therefore, model 2 is introduced, which calculates the current distribution among tapes within a single cable and derives the corresponding loss. In Section III, measured transport AC loss data of single cables are presented, which are compared to the model predictions in Section IV.

II. AC Loss Calculations

A. Model 1: 2D Calculation of Hysteresis Loss in a Three-Phase Cable, Assuming Uniform Current Distribution

The first model uses a simplified two-dimensional representation of the cable, with its cross-section invariant along the length. In other words, the tapes are assumed to be straight rather than twisted. To calculate the current distribution within a tape, it is divided into a number of sub-elements of zero thickness, which carry a uniform surface current density. The sub-elements divide the tape along the width. The elements are then connected in parallel in an electrical network. The resulting network for a 3-tape cable with 3 sub-elements per tape is

Manuscript received 25 September 2023; revised 5 January 2024 and 26 January 2024; accepted 31 January 2024. Date of publication 9 February 2024; date of current version 26 February 2024. This work was supported in part by the French Directorate of General for Civil Aviation, in part by the U.S. Department of Energy, Office of High Energy Physics under Award DE-SC0014009, and in part by ARPA-E under Contract DE-AR0001459. *(Corresponding author: S. Otten.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TASC.2024.3364120.

Digital Object Identifier 10.1109/TASC.2024.3364120

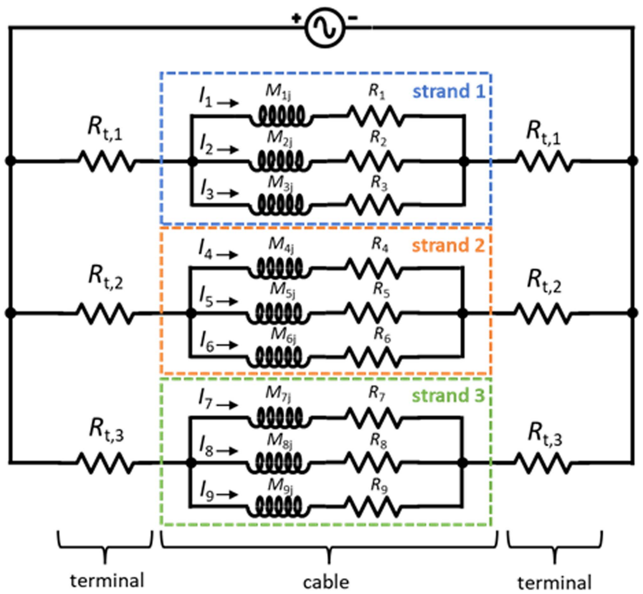

Fig. 1. Network of three strands (tapes) with three sub-elements each. The sub-elements divide the tape along the width. For a three-phase cable this network is repeated three times.

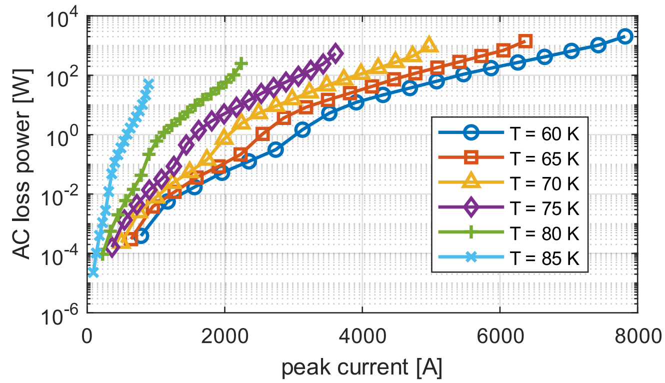

Fig. 2. Calculated AC loss for the 2-meter-long 3-phase AC link at $f = 500$ Hz for different peak current amplitudes and temperaturesInvalid source specified [1]. The distance between the cables is 16.3 mm.

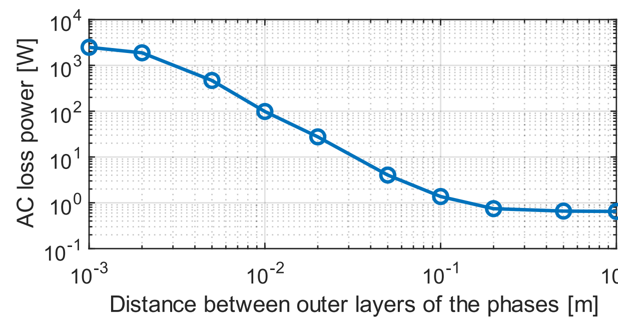

Fig. 3. Calculated AC loss for the 2-meter-long 3-phase cable $I_{\mathrm{peak}} = 2350$ A, $f = 500$ Hz, $T = 77.5$ K, as a function of distance between phases [1].

shown in Fig. 1. All elements are inductively coupled and have a power-law resistance $R \propto J^{n-1}$. Each tape is placed in series with a terminal resistance R_t. Electrical contacts between the tapes are not taken into account. In other words, the inter-strand resistance away from the terminals is assumed to be infinite. Using Kirchhoff's voltage law, an equation for the current in each element can be derived in the following form:

$$\sum_j M_{ij} \frac{\mathrm{d}I_j}{\mathrm{d}t} + \sum_j R_{ij}\, I_j = V(t) \tag{1}$$

In this equation, *I* is a vector of element currents, *M* is the mutual inductance matrix, and *R* represents resistive contributions to the voltage due to the terminal resistance and the power law. In order to impose a sinusoidal current, a voltage of $V(t) = \gamma(I_0 \sin(\omega t) - \sum_j I_j)$ is applied, where I_0 is the current amplitude and $\gamma = 100$ V/A. The equation is solved numerically in MATLAB using the built-in ODE solver ode15s.

AC loss calculations for the baseline cable layout using this method were already presented in our previous publication [1]. This 2-meter-long cable consists of three parallel CORC cables in a triangular configuration, with a distance of 16.3 mm between the surfaces of each pair of cables. This separation is chosen based on the cryostat inner diameter. Each cable contains 8 layers of three 4-mm-wide *Re*BCO tapes on a core with 5.5 mm diameter. The calculation was done using anisotropic critical current data for SuperPower Advanced Pinning *Re*BCO tape from the database of the Robinson Research Institute [8]. Each tape within a cable was assumed to carry an equal current, which was enforced by choosing a high terminal resistance equal for each tape. The calculated AC loss under nominal conditions ($I_{\mathrm{peak}} = 2350$ A, $f = 500$ Hz) at the maximum operation temperature of 77.5 K was 40 W. The predicted AC loss depends strongly depend on the current amplitude, temperature (Fig. 2) and the distance between phases (Fig. 3). The calculated loss is reduced to 0.4 W when the cable is operated at 65 K, the design temperature for the AC link.

B. Model 2: Non-Uniform Current Distribution in a Single Cable

Model 1 assumes that all tapes within a cable carry the same current. However, the tapes in a CORC cable are not fully transposed, and their inductance is not necessarily the same. This can lead to a non-uniform current distribution at high frequencies. The mutual- and self-inductances of the tapes depend on the twist angle and therefore cannot be calculated with the two-dimensional geometry of model 1.

Model 2 aims to assess how the current is distributed among the tapes. It uses a network similar to model 1, but without subdivisions within the tapes. The mutual and self-inductances of the tapes are calculated with the expressions for helical tape conductors derived by T. Tominaka [9]. The diameters and twist pitches used to evaluate the mutual inductance matrix are listed in Table I. These parameters are similar to those of the actual cables in the AC link.

Due to the three-dimensional geometry in this model, the critical current of each tape changes along the length, and cannot be easily implemented in the network. Instead, a cable critical current was estimated by calculating the current distribution

TABLE I
CONFIGURATION OF THE 24-TAPE CORC CABLE

Layer	Number of tapes	Inner diameter [mm]	Twist pitch* [mm]
1	3	5.55	+21.33
2	3	5.68	-20.64
3	3	5.81	+20.06
4	3	5.94	-19.55
5	3	6.07	+19.11
6	3	6.20	-18.73
7	3	6.33	+18.39
8	3	6.46	-18.08

* Twist pitches of different signs indicate twisting in opposite directions

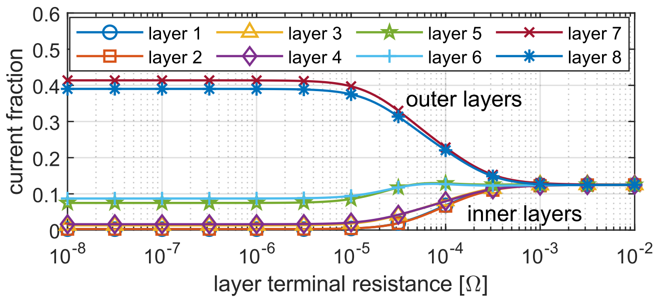

Fig. 4. Calculated current distribution for low current amplitudes at $f = 500$ Hz. Layer 1 is the inner layer, layer 8 is the outer layer.

that satisfies $E = E_c$ in the two-dimensional geometry (cross-section). The tape critical current was estimated by dividing the cable critical current by the number of tapes (24). The tape critical current is assumed to be constant during the simulation.

The calculated current distribution at low current ($I \ll I_c$ in all tapes), is shown in Fig. 4 for a frequency of 500 Hz and a cable length of 2 m. The current fraction in each layer is plotted against the terminal resistance in series with each layer. We can distinguish between two regimes. For high terminal resistances (> 1 mΩ), all layers carry the same current. For lower terminal resistances, the current distribution is determined by the mutual inductance matrix. The outer layers carry a disproportionately large fraction of the current. This can be seen as a form of skin effect. We observe that the outer two layers carry similar amounts of current, since they are twisted in opposite direction, and thus cancel out each other's axial magnetic field. This way, the two outer layers together form a low-inductance path. A typical terminal resistance is <<1 μΩ and thus falls in the inductance governed regime. An excess current in the outer layers was also found by Michael et al., who calculated the current distribution in fast-ramped CORC cables [10].

Fig. 5 shows the calculated layer current as function of time for 800 A and 2400 A peak currents. The calculation assumes zero terminal resistance. At 800 A, the layer current remains below the layer critical current of 366 A at all times, and the relative current distribution does not change with time. At 2400 A, the critical current is quickly exceeded in layers 7 and 8, followed by a rapid rise in current in layers 5 and 6 until their critical value is also reached. As the critical current is exceeded, the tapes dissipate heat. This is an additional AC loss mechanism, not captured by model 1.

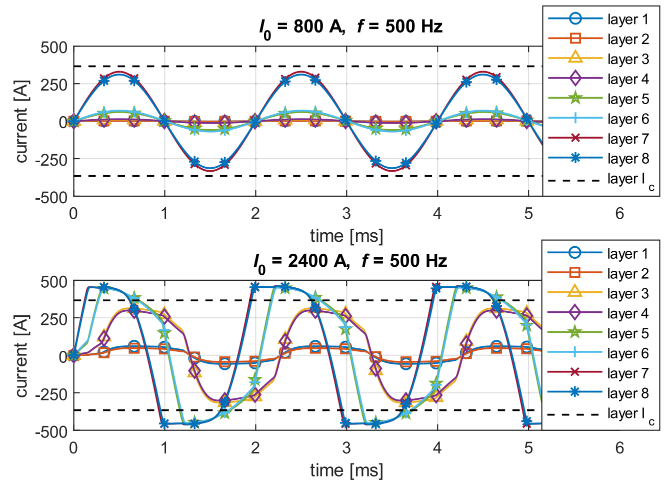

Fig. 5. Calculated layer current distributions at 800 A and 2400 A peak amplitude. Layer 1 is the inner layer, layer 8 is the outer layer.

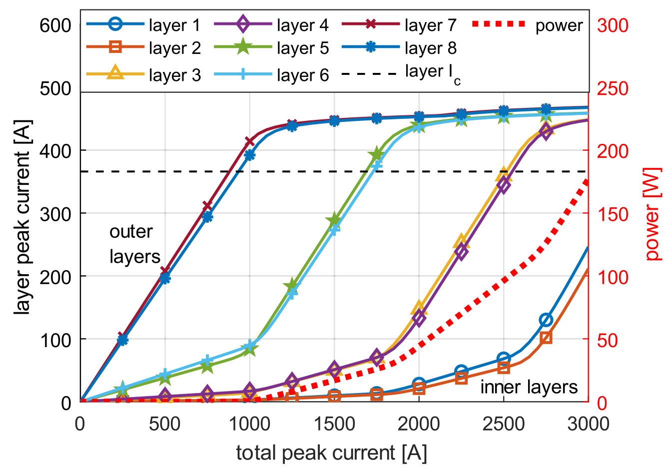

Fig. 6. Calculated peak currents and AC loss at $f = 500$ Hz as a function of peak current amplitude. These data are calculated using model 2, which assumes a uniform current density within each strand.

The calculated layer peak currents and AC loss for this 2-m-long single cable are shown in Fig. 6. For total peak currents below 800 A, the critical current is not exceeded in any layer. The current distribution is thus fully determined by the mutual inductance matrix. As a result, the fraction of current carried by each layer does not depend on the total peak current. For total peak currents above 800 A, the critical current is exceeded in at least one layer, and the current distribution is no longer constant.

III. AC LOSS MEASUREMENTS

A. Measurement Set-Up

The transport AC loss was measured on several single CORC cables in liquid nitrogen in a non-conducting, non-magnetic container. The sample current is provided by a 50 A power supply connected via a 65:2 transformer. The transport loss $P = IV\cos(\phi)$ is found by measuring the amplitude (RMS) of current I and voltage V, as well as the phase shift ϕ between them. The voltage is measured using voltage taps installed inside the

TABLE II
CABLE SAMPLES FOR AC LOSS MEASUREMENT

	Sample 1	Sample 2
Core material and diameter	Cu Ø4.3 mm	Al Ø5.5 mm
Number of *Re*BCO tapes	16	24
Number of layers	8	8
Terminal length	200 mm	150 mm
Cable length between terminals	610 mm	593 mm
Type of solder in terminals	Indium	Indium
Insulation	0.05 mm polyester	1.0 mm polyimide + 0.05 mm polyester
Critical current at 77 K	1.39 kA	2.48 kA

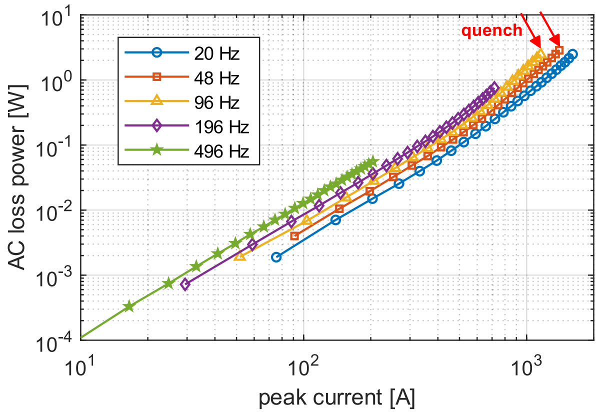

Fig. 7. AC loss measurements of sample 1.

terminations. Its amplitude and phase are recorded with a lock-in amplifier (SRS SR860). A Rogowski coil with a second lock-in amplifier is used to find the amplitude and phase of the current.

B. CORC Samples 1 and 2

The properties of the two cables and their measured critical currents (I_c) are listed in Table II. Sample 2 is the most similar to the 24-tape cables that are used in ASCEND and has thick electrical insulation. Sample 1 is a smaller 16-tape cable and does not have any electrical insulation apart from a thin polyester heat shrink tube. Voltage taps are positioned in the copper terminations. The measured AC loss can thus include contributions both from the cable and the terminations, so that linear scaling with cable length cannot be proven. For this reason, we present the results in units of W rather than W/m.

C. Measurement Results

The AC loss was measured at frequencies of 20, 48, 96, 196 and 496 Hz. The results are shown in Fig. 7 for sample 1 and Fig. 8 for sample 2. At low amplitudes ($I \ll I_c$), a loss scaling of $P \propto I^2 f^{0.5}$ is observed, while at higher amplitudes, the current scaling increases to $I^{3.0\pm0.5}$. For amplitudes exceeding 1 kA, the AC loss of sample 2 is some 20 to 40% lower than the AC loss of sample 1.

At 20 Hz, the maximum set-up current of 1.6 kA peak amplitude could be reached. At 48 Hz, the cables quenched at peak currents of 1.45 kA (sample 1) and 1.44 kA (sample 2),

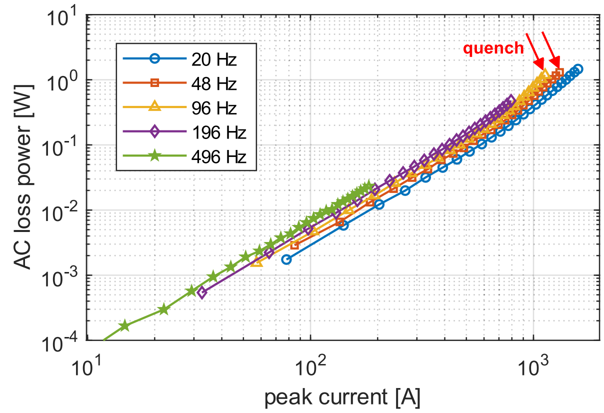

Fig. 8. AC loss measurements of sample 2.

TABLE III
PEAK CURRENT AT QUENCH

Frequency	Sample 1	Sample 2
DC	1.65 kA	2.63 kA
48 Hz	1.45 kA	1.44 kA
96 Hz	1.21 kA	1.19 kA

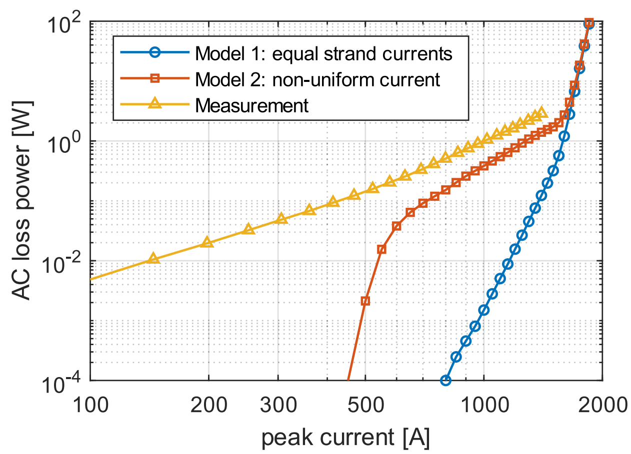

Fig. 9. Comparison of AC loss calculation and measurement for sample 1 at 48 Hz.

while at 96 Hz the quench currents were 1.21 kA and 1.19 kA. The quenches were marked by a rapid rise in voltage to levels exceeding 40 mV, which tripped the quench protection system. These quench currents are lower than the measured critical currents and DC quench currents (see Table III). At 196 Hz and 496 Hz, the maximum currents were again limited by the set-up compliance, and the quench current could not be reached.

IV. DISCUSSION

The measured AC loss of sample 1 at 48 Hz is compared to the calculated AC loss in Fig. 9. Both calculations are done with a measured critical current of 1385 A. The measured AC loss is significantly higher than both model predictions, although the difference with model 2, which takes into account a non-uniform current distribution, is smaller.

The difference suggests the presence of another contribution to AC loss that is not included in either model. The frequency and current scaling at low amplitudes of $P \propto I^2 f^{0.5}$ are typical for eddy current loss in a metal volume thicker than the skin depth δ. For copper at 77 K, δ is 1–5 mm for the frequencies considered. Thicker metal layers are indeed present in the cable core and the current terminals. To distinguish between contributions of the terminals and the cable itself, future measurements are planned with additional voltage taps away from the terminals.

In addition to eddy currents within metal volumes, currents may flow through inter-strand contacts. The magnitude of these currents and associated coupling loss depend on inter-strand resistance (ISR), which were not analyzed in this work.

Also, the origin of the quenches is to be further investigated. The quenches occur well below the critical current, and the quench current decreases with frequency. Therefore, we suspect that they are caused by a combination of relatively high AC loss and thick thermal insulation, which leads to thermal runaways. The location of the initial hot spot could be localized with additional voltage taps along the cable. However, this requires the partial removal of the electric insulation, which alters the thermal properties of the cable.

V. Conclusion

Using a network approach based on 2D geometry (model 1), a hysteresis AC loss of 40 W was found for the three-phase AC link based on *Re*BCO CORC cables. This loss value was calculated assuming a separation between phases of 16.3 mm, a temperature of 77.5 K and a 500 Hz applied current with 2350 A peak amplitude. The model predicts that hysteresis loss is reduced significantly when increasing the distance between the phases or reducing the temperature.

The current distribution between the tapes in the cables was calculated using mutual inductance matrices for helical tape conductors (model 2). This model predicts that, at 500 Hz, the outer two layers of a CORC cable carry a disproportionate fraction of the current (skin effect). This can lead to additional AC loss if the critical current in the outer layers is exceeded.

The measured AC loss in single cables exceeds the calculated AC loss of both models. Also, quenches were observed at currents well below the critical current at 48 Hz and 96 Hz. The quench current was found to decrease with increasing frequency.

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