

# The electrical aspects of the choice of former in a high $T_C$ superconducting power cable

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**Abstract** — Centrally located in a superconducting power cable the former supplies a rigid means onto which to wind the superconducting tapes and enables a continuous supply of cooling power via a flow of liquid cryogen through it. Therefore, the choice of former has a broad impact on the construction and design of a cable. The diameter of the former determines the overall diameter of the total cable, influences the heat loss to the ambient and enters into the total AC-losses. Depending on whether the former is made of a good or poor electrical conductor eddy currents in the former itself may also contribute significantly to the AC-loss of the cable; the choice between an open and a closed former determines how and where the pressure load (pressurized coolant) has to be accommodated. In this work the electrical impact of the choice of material and diameter of the former on the AC-loss of a cable conductor is addressed.

## I. INTRODUCTION

A future superconducting power cable may be based on a centrally located semi-infinite tube/pipe, a so-called former. Mechanically it supports the superconducting tapes and because it is hollow it can be exploited for cooling using liquid cryogen. The use of many different materials for the former has been reported: aluminium [1], copper [2], stainless steel [1], [3], polyethylene [4], [5], all having varying diameters (mm): 19 [2], 24.4 [7], 27.0 [8], 30 [6], 40 [9], 45.2 [4].

The following terminology is used through out the paper; a superconducting layer is defined as a cylindrical shell of superconductors filled with a finite number of superconducting tapes usually such that the shell is fully covered (no space between tapes) or such that the tapes are equally spaced.

### A. Material

Each superconducting layer leading an AC current contributes to an axial field (if helically wound) in the centre of the former. The resulting magnetic field obtained from a multitude of layers is said to be unbalanced if this is nonzero.

The unbalanced field occur due to an uneven current distribution between two or more layers. In a real conductor this is typically the case.

Such an axial field would induce eddy currents in an electrically conducting former.

Here we present data on a one layer conductor which is supported by a glass fibre reinforced polymer former (GFRP), in which different former candidates with smaller diameter have been inserted. Assuming that the transport current only induces an axial field inside the GFRP former the measurements have been compared with a full numerical solution of the theoretical model.

The measurement confirms the  $I_{rms}$  squared dependency of the eddy current loss predicted by the model, however, there are some discrepancies in the quantitative numbers.

Further, the axial field in a four layer model has been measured with a pick-up coil in several places along the cable conductor in order to estimate the magnitude of the field.

Also tangential field and radial field components occur when the former does not 'see' an ideal homogeneous current sheet, due to uneven current distribution between neighbouring tapes in one layer and due to a finite spacing between each tape. However, these fields are negligible with respect to eddy current losses in the former [9].

It is the purpose of this contribution to discuss the magnitude and the relevance of unbalanced axial magnetic field as a source of electrical loss.

### B. Diameter of former

Apart from the influence the choice of material has on the AC-losses, also the diameter of the former has an impact on the AC-losses.

Approximating the AC-loss,  $P_{hys}$ , in a cable conductor with the monoblock model [10] it appears that, if normalised to  $I_C$ , the AC-losses are independent of the diameter. However, if one require the total  $I_C$  of the conductor to be the same,  $J_e$  would need to be higher for the superconducting "shell" in the former with the smaller diameter (where  $J_e$  is the engineering current density). Using commercially produced tapes it is not simple to increase the  $J_e$ . Instead, the same number of tapes would be required in order to obtain a certain nominal  $I_C$ , independent of the diameter of the former. This leads to a relatively thicker current carrying layer for the smaller former compared to the larger. According to the monoblock model the loss depends linearly on the thickness of the current carrying sheet through the geometrical factor,  $h$

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$= (R_o^2 - R_i^2)/R_o^2$  where  $R_o$  and  $R_i$  are the outer and inner radii of the current sheet.

The relation between the loss and the diameter of the former was investigated using three single layer cable conductors. The results was in accordance with the prediction of the monoblock model.

Results on a 4 layer conductor indicated an electrical degradation of the outer layers due to a magnetic field created by the inner layer(s) carrying a current. This, however, the monoblock does not take into account.

The latter result could be as important in an optimisation of the layer current distribution as the resistance and inductance of the system.

## II. THEORETICAL MODEL

### A. Axial field

An unbalanced axial magnetic field  $H_a$ , in a helically wound conductor with one or more layers can be expressed as:

$$H_a = \sum_n I_n / L_{pn} \quad (1)$$

where  $I_n$  is the current in the  $n^{\text{th}}$  layer and  $L_{pn}$  the winding pitch (finite) of the corresponding coiled superconducting layer.

In a simple model the induced axial magnetic field can be regarded as an external magnetic field  $B_{\text{ext}} = \mu_0 H_a$  applied on a circular section of the former tube (rod) where  $\mu_0 = 4\pi \cdot 10^{-7}$  Vs/A·m is the vacuum permeability. If a full analysis is made [11] one arrives at a solution for the current density distribution in the conducting insert (former candidate) that is:

$$J(r) = \frac{k}{\mathbf{m}} \cdot \frac{B_{\text{ext}}}{J_0(k \cdot r)} \cdot J_1(k \cdot r) \quad (2)$$

where  $J(r)$  is the current density in a point of distance  $|r|$  to the centre of the cylinder,  $k = \sqrt{-i\omega\mu_0\mathbf{s}}$  (where  $i = \sqrt{-1}$ ),  $\omega$  the driving frequency of the current/magnetic field,  $\mathbf{s}$  the electrical conductivity and  $J_n$  is the Bessel function of the first kind of order  $n$ .

The power dissipation of the conducting insert can be found by integrating the current distribution multiplied by the electrical field over the wall thickness, i.e.  $R_i \leq r \leq R_o$  where  $R_i$  and  $R_o$  are the inner and outer radii respectively of the conducting insert. This leads to the following expression for the resulting power dissipation,  $P(I_{\text{rms}})$ , per unit length,  $l$ , which can be solved numerically:

$$\frac{P(I_{\text{rms}})}{l} = \frac{2\mathbf{p}\mathbf{r}}{L_p^2} \cdot I_{\text{rms}}^2 \cdot \int_{R_i}^{R_o} r \cdot \left| \frac{k \cdot J_1(k \cdot r)}{J_0(k \cdot r)} \right| \cdot dr \quad (3)$$

where  $\mathbf{r} = 1/\mathbf{s}$  is the resistivity. The solution leads to an  $I_{\text{rms}}$  squared dependency of the induced eddy current loss in the former candidates.

### B. The monoblock model

In one model the AC-losses per unit length for a conductor driven below its  $I_C$  is set equal to the hysteresis losses,  $P_{\text{hys}}$ , per unit length,  $l$ , in the superconducting layer. This is the so called monoblock [10] which can be written;

$$\frac{P_{\text{hys}}}{l} = \frac{\mathbf{m}_0}{2 \cdot \mathbf{p}} \cdot f \cdot \frac{I_C^2}{h^2} \cdot \{2 \cdot (1-i \cdot h) \cdot \ln(1-i \cdot h) + (2-i \cdot h) \cdot i \cdot h\} \quad (4)$$

where  $f$  is the driving frequency of the current,  $I_C$  is the total critical current of the conductor,  $i$ , is the reduced current  $I_{\text{peak}}/I_C$  and  $h = (R_o^2 - R_i^2)/R_o^2$  is the geometrical factor.

In (4) it is observed that the loss depends on the geometrical factor linearly and if normalised to  $I_C$  depends on the current  $I_{\text{peak}}$  to the third. The diameter of the former appears not to be relevant, however, at  $I_{\text{peak}}$  below  $I_C$  the geometrical factor  $h$  is approximately proportional to the thickness of the current sheet, which again is inverse proportional to the size of the diameter (assuming the use of commercially available tapes). Thus the diameter of the former influences the AC- loss indirectly through the geometrical factor  $h$ .

## III. EXPERIMENTAL

Several short one layer conductors (about 1 m) were constructed, sample A, B, C, D. And one 3 m conductor with 4 layers was used, sample E. All conductors were hand wound. Terminations of Cu were soldered to the superconducting tapes keeping the temperature low ( $<200$  °C) and the heating time short (5-10 minutes). Data for the used conductors are given in table I. The cooling procedure was performed such that the former was cooled down first (before the tapes) in order to minimise the thermal mismatch strain between the tapes and the former, further, the cool down was done over a suitable time span to avoid large temperature gradients.

TABLE I  
EXPERIMENTAL CABLE CONDUCTORS

sample	length [cm]	pitch [cm]	diameter [mm]	number of tapes	DC $I_C$ [A] (1 $\mu$ V/cm)
A	109	51	40	32	300
B	114.5	infinite	24.4	27	286
C	118.5	infinite	40	44	484
D	118	infinite	14.5	16	187
E	300	32	40	159	1590

Infinite pitch corresponds to the superconducting tapes being parallel with the former axis.

For the electrical measurements a conventional lock-in circuit [9] was used. The feed current was generated by a sine generator that was connected to a power amplifier and a transformer. The current was probed by a Rogowski coil. The in-phase voltage over the superconductor was measured with the lock-in amplifier and the loss calculated on the basis of the measured current and the measured voltage. The signal

from the Rogoski was used as reference for the lock-in amplifier.

Unless otherwise stated, all measurements were done at 77 K and 48 Hz. The AC-loss measurement, the phase calibration and the  $I_C$  measurement (1  $\mu\text{V}/\text{cm}$  criteria) were all done in the same cool down.

In order to probe different former material for eddy current loss the AC-loss curve was first recorded with an empty former, then, in turn each of the former candidates was inserted and the corresponding AC-loss curve recorded. Finally, another AC-loss measurement was done in order to detect any drift in the experimental set-up.

#### IV. RESULTS AND DISCUSSION

##### A. Material

In Table II the eddy current losses measured at 48 Hz using sample A are given for some of the former candidates at  $I_{\text{rms}} = 300$  A. In Fig. 1. the measured AC-losses are shown for the Cu tube and the Al rod together with the theoretically calculated eddy current losses according to (3). The total loss of the cable conductor at 300 A is about 0.3 W (48 Hz and zero external magnetic field) and the spread of the measurement is 0.01 - 0.02 W, i.e. roughly 5%. Other materials, such as stainless steel, have been tested as well but only the Cu tube, brass tube #1 (largest diameter), the Al rod and the combined Al-helix/Cu-braid showed a significant loss. As the eddy current losses scale with  $I_{\text{rms}}^2$ , the losses of some of the other former candidates could be distinguishable at lower currents, e.g. 100 A, because the dominating hysteretic losses falls off faster, roughly with  $I_{\text{rms}}^3$  [10] at the low current end. However, the spread of the loss measurement increases, e.g. at 100 A, roughly to 15%, thus preventing us from detecting the eddy current losses at the low current end.

TABLE II  
FORMER CANDIDATES

Former candidates	former diameter [mm]	wall thickness [mm]	$\rho$ @ 77 K [ $\Omega\cdot\text{m}$ ]	Loss @ 300 $A_{\text{rms}}$ [W]
Copper (Cu) 9	28	1.15	$5.9 \cdot 10^{-9}$	0.060
Aluminium rod	28	14	$1.8 \cdot 10^{-8}$	0.036
Brass tube #1	32	1.3	$4.4 \cdot 10^{-8}$	0.027
Brass tube #2	29	0.5	$5.1 \cdot 10^{-8}$	-
Cu-braid + Al-helix	34	1.5	-	0.029

Tested former candidates, all with a length of about 1 m. The uncertainty of the loss measurement at 300 A is 0.01 - 0.02 W. The '-' indicates no available data or values below level of sensitivity.

The maximum loss is around 0.1 W which is detected for the Cu tube above 300 A. It is obvious that the good electrical conductors made of aluminium and copper show the largest contribution to the AC-loss, but also the loss contribution of the large diameter brass tubes and the combined Al-helix + Cu-braid (open former candidate) is significant.

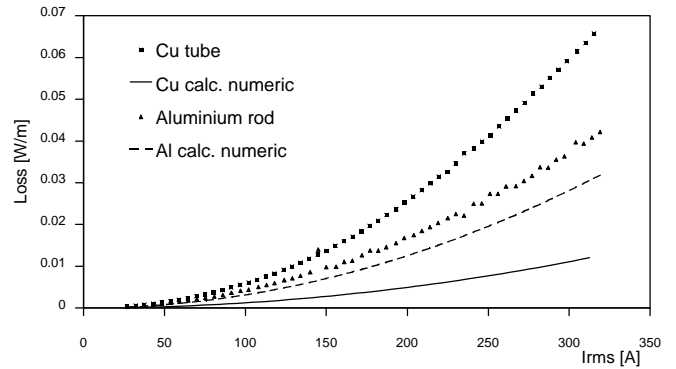


Fig. 1. Measured and calculated loss in two metal inserts @ 48 Hz.

As expected the  $I_{\text{rms}}$  squared law applies to the metal inserts and the quantitative values fit within a factor of 2-3 with the calculated ones. The match between the calculated and measured curve is better for the Al rod than the Cu tube. The observed discrepancy in the quantities can be explained in several ways. The differences could originate from a non recognised tangential field. However, detailed calculations show that the tangential field from the finite size superconducting tapes does not contribute significantly ( $\mu\text{W}$  range). Thus, the tangential field stemming from an uneven current distribution between each tape due to e.g. varying contact resistance and possibly an end effect must account for the remaining part of the deviation.

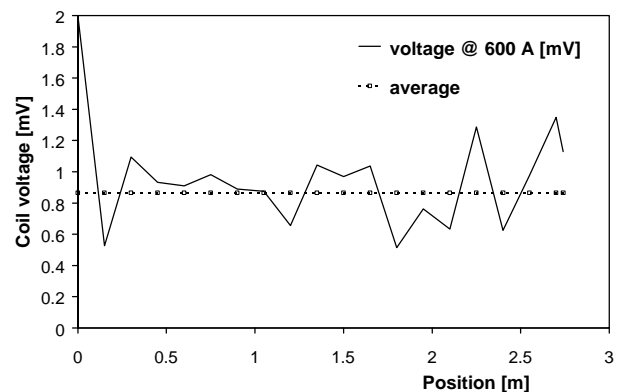


Fig. 2 Coil probe voltage @ 48 Hz for 600 A

In order to estimate the importance of the axial field this was measured in the centre along the whole length of sample E (four layer model) with a pick-up coil having 42 windings, being 23.3 mm long and having a diameter 29.5 mm. The axial field is proportional with the voltage over the coil, the latter is plotted in Fig. 2. An average of roughly 0.9 mV is indicated (dashed line) excluding the end values (inhomogeneous field due to terminations). The field varies along the length more than a factor two which is surprising given that the four layer model was forced to have practically same current passing in each of the four layers, further, the pitch and superconducting tape coverage was as homogeneous as one could get it.

Based on the presented data the significance of the eddy current losses has to be considered seriously when using formers of pure Cu or Al. If a high purity Cu tube is used, which has a lower resistivity than our test Cu tube, this may lead to eddy current losses beyond the 0.1 W at 300 A. In a cable designed for 2 - 5 kA potentially large unbalanced magnetic field can be expected given the apparent inhomogeneity along the conductor and the varying current distribution in the layers depending on the load of the cable. In this scenario the eddy current losses could become comparable to the heat in-leak and the hysteretic losses.

### B. Diameter of former

Fig. 3. shows three different samples, B, C and D having different former diameters. According to the monoblock model, which is also plotted in Fig. 4. no difference should be observed between the three conductors. At low reduced current  $I/I_C$  this holds within a factor of 7 and becomes better at higher currents close to  $I_C$ . The loss curves for the three conductors partly fall on top of each other, however, large deviations are likely to occur due to the many factors. More homogeneous current distribution was expected and seen (monitored for sample D) when loss curves were recorded at higher frequencies (480 Hz). The more homogeneous current distribution lead to a slight decrease of the loss per cycle in sample B and D. The loss measurement were very sensitive to an offset in the current probe and to the way the contribution from the resistive current leads were subtracted.

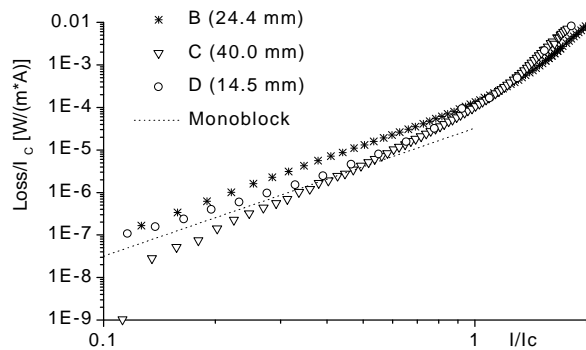


Fig. 4. AC-loss @ 48 Hz for sample B, C and D normalised to  $I_C$

On sample E, a decrease of up to 20% in the outer layer was observed when large current passed through the inner layers. In relation to the diameter of the former this also needs to be considered as it is not part of the monoblock model.

### V. CONCLUSION

We have studied the loss characteristic of two former parameters which may become important in a future superconducting power cable; the choice of material and the diameter of the former.

Eddy current losses in conductive former candidates have been measured and compared with a model. Quantitatively the measurement lies a factor 2-5 above the prediction of the

model. The discrepancy observed may be explained by either an end-effect, or by an unexpected extraordinary inhomogeneous field.

Experimentally we found that only materials with low resistivity may under certain circumstances significantly contribute to the total AC-losses in a superconducting cable (compared with hysteretic losses which is around 1 W/m close to  $I_C$  [12], [13] for 2 - 5 kA superconducting cables).

Additionally, the unbalanced axial field of a four layer model has been probed.

Loss measurement on single layer conductors with different diameters was in agreement with the monoblock model. No variations could be detected due to variations in the former diameter when the loss is normalised to  $I_C$ . A decreased in the performance of the conductor can be expected if the size of the former leads to the need for extra superconducting layers, partly due to the linear dependency on the superconducting layer thickness, partly due to the decrease if  $I_C$  in the outer superconducting layers related to a magnetic degradation.

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