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Loss and Inductance Investigations in Superconducting Cable Conductors

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Abstract

An important parameter in the design and optimisation of a superconducting cable conductor is the control of the current distribution among single tapes and layers. This distribution is to a large degree determined by inductances, since the resistances are low. The self and mutual inductances of the layers are therefore studied theoretically. The current distribution between the superconducting layers is monitored as a function of transport current, and the results are compared with the expected current distribution given by our equivalent electrical circuit model.

The AC-losses are measured as a function of transport current and current distribution.

This presentation is based on a number of experiments performed on prototype superconducting cable conductors. The critical current (1 μV/cm) of the conductor at 77 K (-196 °C) was 1590 A (cable #1) and 3240 A (cable #2) respectively.

At an rms current of 2 kA (50 Hz) the AC-loss was measured on cable #2 to 0.6 W/m·phase. This is, to our knowledge, the lowest AC-loss (@ 2kA & 77 K) of a high temperature superconducting cable conductor reported so far.

1. Introduction

The AC and DC performance of the cable conductor in a future superconducting power cable is obviously of great interest when this new type of power cable is developed. An important parameter in the design and optimisation of the conductor is the loss as a

function of current distribution in long conductors [1]-[3]. For this reason the parameters that determine the current distribution are studied.
Measurements of conductor losses in two cable conductor prototypes are presented. The data for the conductors are shown in table 1.
This paper aims at giving an overview on the factors important in the development of a superconducting cable conductor for a transmission cable. Fault and over currents in superconducting cable conductors are briefly considered.

Table 1
Relevant cable data

	Cable #1	Cable #2
Number of layers	4	8
Length	3 m	10 m
Winding pattern	+ – + –	
Winding pitch (winding angle)	320 mm (21.4°)	Variable
Number of tapes	159	193
Former diameter	40 mm	35 mm
Outer diameter	44 mm	40 mm
Total critical current; $I_{C,total}$	1590 A	3240 A

2. Conductor geometry

The basic components of the cable conductor are the superconducting tapes. The superconducting material is $Bi_2Sr_2Ca_2Cu_3O_{10}$ imbedded in a silver matrix (see fig. 1). The superconducting tapes are manufactured and sold by the Danish company NST[1].

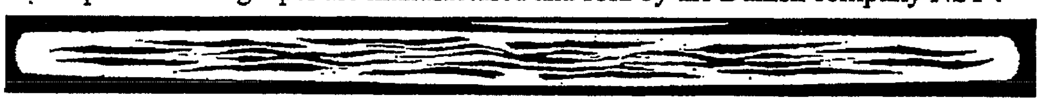

Fig. 1: Cross sectional view of a superconducting BSCCO-2223 tape with 19 filaments. The dimensions are 3.5×0.2 mm. The dark area inside the bright grey area (silver metal matrix) is the actual superconducting material carrying the current.

The tapes require cooling to a temperature below 110 K in order to become superconducting. This is done with liquid nitrogen (LN_2), implying that a superconducting cable needs a thermal insulation (cryostat) besides the electrical insulation.
The critical current serves as a measure for the current carrying capacity of the cable. The critical current is defined as the DC current necessary to cause an electric field in the cable of 1 μV/cm.
Basic information about the overall cable design, superconductivity and insulation considerations were presented at NORDIS 1996 by Tønnesen [4].
An example of the geometry of the cable conductor is schematically presented in fig. 2. The tapes are helically wound around a central tube (former). The helical winding

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enables the finished cable to be bent without mechanical and electrical degradation of the superconducting tapes. Furthermore, the helical winding provides us with means of controlling the distribution of current between the single layers of tapes (this is discussed in section 3).

Between the single layers of tapes an insulating layer of Mylar is placed. This minimises induced currents circulating between layers of tapes.

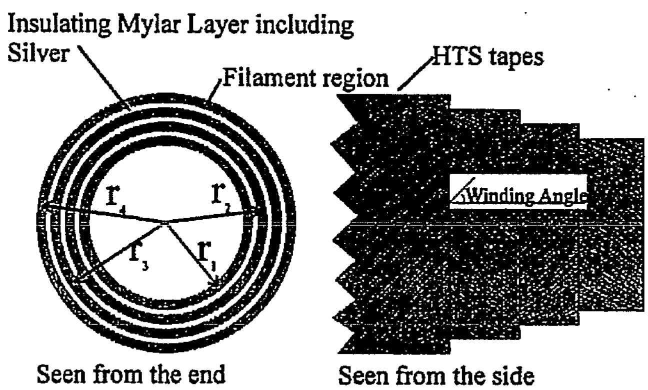

Fig. 2: Schematic view of the winding in a four layer cable conductor. (This corresponds to cable #1)

3. Current distribution in cable conductors

In long length superconducting cables the self- and mutual inductances between the layers determine the distribution of AC-current between layers. In short laboratory models however, the joint resistance in series with each layer also influence the current distribution.

For DC-currents the joint resistances determine the current distribution.

3.1 Self and mutual inductance of the layers

In the following the self and mutual inductance are stated per unit length of conductor. The thickness of the individual layer is regarded infinitesimal. Furthermore, the winding with discrete tapes is modelled by a continuous current sheet. Detailed derivations of the expressions are found elsewhere [3].

The layer self inductance per length conductor is given by the equation

$$L = \mu_0 \cdot \frac{\pi \cdot r_i^2}{L_{pl}^2} + \mu_0 \cdot \frac{\ln\left(\frac{D}{r_i}\right)}{2 \cdot \pi}, \qquad (1)$$

where L_{pi} is the winding pitch of the layer given from the winding angle, α ($\tan(\alpha)=2\cdot\pi r_i/L_{pi}$), r_i is the radii of the layer and μ_0 is the vacuum permeability ($4\cdot\pi\cdot10^{-7}$ H/m). D is the distance between the layer and the centre of the return path.

The layer mutual inductances per unit length conductor are given by the equation

$$M_{i,j} = M_{j,i} = \frac{a_i \cdot a_j \cdot \mu_0}{L_{pi} \cdot L_{pj}} \cdot \pi \cdot r_i^2 + \frac{\mu_0}{2\cdot\pi}\ln\left(\frac{D}{r_j}\right) \quad \text{for } r_j > r_i \,, \qquad (2)$$

where a_i and a_j are constants (+1 or -1) taking into account the relative winding directions. If the two layers are wound in the same direction around the former the sign of the constants are the same. In the case of opposing twist the constants have opposite sign.

3.2 The equivalent electrical circuit model

The steady state current distribution in a superconducting cable conductor can be determined by solving (3) in the case where the voltage drop (e_i) across each layer is identical ($e_1=e_2=...=e_n$).

$$\begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix} = j\cdot\omega\cdot \begin{bmatrix} L_1 + \frac{R_1}{j\cdot\omega} & M_{2,1} & \cdots & M_{n,1} \\ M_{1,2} & L_2 + \frac{R_2}{j\cdot\omega} & \cdots & M_{n+1,2} \\ \vdots & \vdots & \ddots & \vdots \\ M_{1,n} & M_{2,n} & \cdots & L_n + \frac{R_n}{j\cdot\omega} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} \qquad (3)$$

The R_i term in (3) takes into account the joint resistance and the AC-loss of the individual layer. ω is the angular frequency ($2\cdot\pi f$) and j is the imaginary unit.
The current will begin to redistribute when the critical current in a layer is reached. Thereby the critical current of the layers also can play a direct role.

3.3 Measurement of current distribution

The current in the individual layer can be monitored with torroidal Rogowski coils placed around layer 1 (inner layer), layer 2 and 3 and so forth. The measured current distribution for cable #1 as a function of the total current at 50 Hz is shown in Fig. 3 as an example. Also shown is the calculated current distribution taking the calculated self/mutual inductance and the measured joint resistance into account. The measured current distribution agrees well with the calculated one at currents below 1000 Arms. At AC peak currents above the critical current for each layer the superconducting layers develop a voltage drop, i.e. causing a redistribution of the current. This is observed in fig. 3 for currents above 1000 Arms.

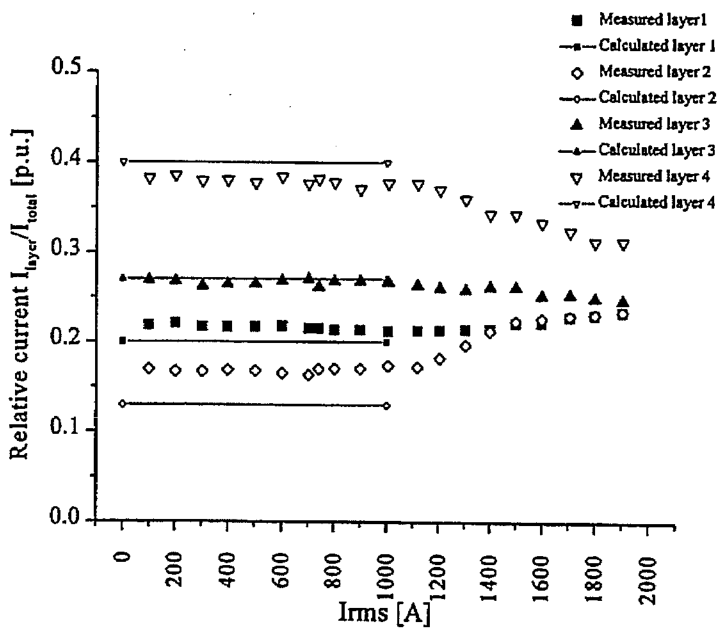

Fig. 3: Measured relative current vs. total current.

A solution to the current distribution in cable #1, using only inductances and neglecting joint resistances in the calculation does not fit with measured data. In fact this calculation results in current running in the opposite direction for layer 2 (19 %).

Generally most of the current tends to run in the outermost layer 4 (70 %) and a smaller fraction in layer 3 (43 %). Layer 1 would carry only a low current (6 %). Cable conductors where even current distribution is the goal are currently designed by adjusting the inductances e.g. pitch, winding pattern etc. Even current distribution is predicted to exhibit the lowest conductor losses obtainable at nominal current.

4. Losses in superconducting cables

In a superconducting cable there are a number of sources for losses. First of all, losses occur due to heat in-leak through the thermal insulation. The thermal insulation is made of concentric pipes with vacuum in between. In order to minimise heat in-leak by radiation, reflecting foils (multi layer super insulation) are placed in the vacuum space between the two pipes. The heat in-leak is expected to be of the order of 1-2 W/m·phase [5].

In the electric insulation dielectric losses occur just like in conventional cables. These losses are small compared to the heat in-leak and the conductor losses.

The losses in the conductor occur partly in the silver matrix and partly in the superconducting material as a result of the current flowing. The losses in the silver matrix are "coupling losses" where current is transferred from one superconducting filament to another, and eddy current losses. These losses are negligible compared to the loss in the superconducting material and the thermal in-leak. The loss in the superconducting material at low current is completely dominated by hysteretic loss. At higher currents i.e. near and above the critical current, a resistive loss is generated as the cable gradually leaves the superconducting state.

The hysteretic losses are a result of the magnetic field lines (caused by the current) moving in and out of the superconducting material. Vellego and Metra [6] have given a simple expression (4) for calculating the hysteretic loss in a superconductor shaped like a cylindrical tube. This model is generally referred to as the Monoblock model. The expression is shown here as it gives an impression of which factors have an influence on the loss.

$$P_{Monoblock} = \frac{\mu_0 \cdot f I_c^2}{2\pi \cdot h^2}\{(2-Fh)Fh + 2(1-Fh)\ln(1-Fh)\} \approx \beta \cdot \frac{\mu_0 \cdot f \cdot h \cdot I_P^3}{2\pi \cdot I_C} \qquad (4)$$

Here $F = I_p/I_c$ is the ratio between the peak current and the critical current, f is the frequency, and $h = (D_o^2-D_i^2)/D_o^2$ inner and outer diameters of the superconducting tube. β is a factor of proportionality.

From expression 4 it is deduced that the hysteresis loss is decreased by larger critical current, thinner superconducting layer and low current.

If the conductor is used for DC there will be no losses in the conductor. In this case, only the thermal loss is significant. This would of course make superconductors interesting for use in DC cables. It is however expected that AC cables will be the first application in power transmission as these cables generally are shorter than DC cables.

The losses generated at low temperature have to be removed by a cooling machine. Taking into account the Carnot factor and the efficiency of the cooling machine a penalty factor in the range of 10-15 has to be introduced. I.e. it takes 10-15 watts to remove 1 watt generated at 77 K. It is thus important to keep the losses low at 77 K.

4.2 Measurement of AC-losses in cable conductors

The main goal of designing the cable conductor is to minimise the conductor loss at nominal current. The nominal current is a chosen current below the critical current. In order to evaluate the loss in the cable conductor under AC-current a set-up for measuring losses is needed.

AC-loss measurements can be performed in a number of ways. Calorimetrically using boil-off thermometry [5], [7], magnetically, with a resonant circuit [8] or electrically with a phase sensitive device [5], [9]. Here, the electric method using transport current is exploited.

The electrical AC-loss measurement is based on the four-terminal principle. An AC current, I, is applied to the conductor, the voltage, U, across the conductor and the voltage-current phase difference, φ, is measured with a digital lock-in amplifier (a phase sensitive voltmeter). The AC-loss is calculated as the product of the resistive (in-phase) voltage and the total current (rms values).

Fig. 4 shows measurements performed on the two cable conductor prototypes treated here. The measurements are performed at 50 Hz. Also shown on fig. 4 is the Monoblock model prediction for the loss.

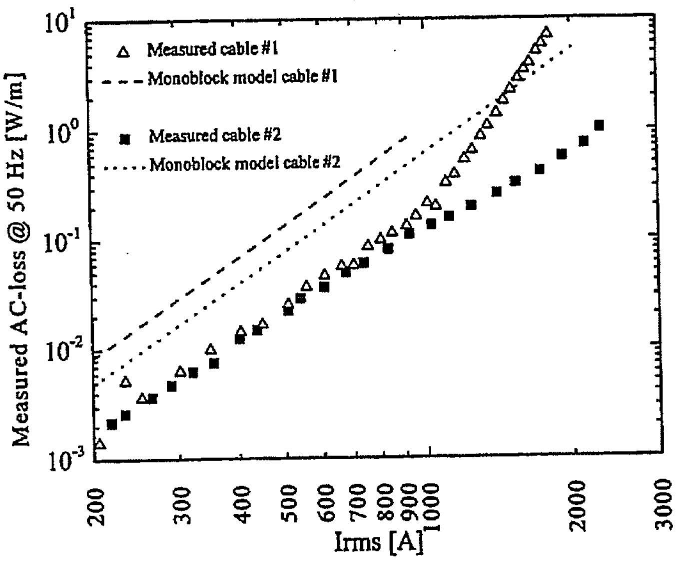

Fig. 4: Measured AC-loss in two cable conductor prototypes

It appears that the measured loss is roughly 5 times smaller than the calculated loss. The reason for this is a more favourable current distribution than assumed in the loss model.

In cable #1, this is obtained by forcing an equal current distribution with the joint resistances, which is clearly not desirable as it results in additional loss in the joint.

In cable #2 the current distribution is made favourable by adjusting the self and mutual inductances. Thus cable #2 has a realistic design for a superconducting cable conductor. The conductor has a loss of only 0.60 ±0.1 W/m·phase @ 77 K at the expected nominal current of 2 kArms, even though the peak value of the nominal current is close to the critical current of the conductor.

We therefore now have a low loss conductor design suitable for a superconducting cable where the conductor loss is significantly lower than the expected heat in-leak. We now have a low loss conductor design suitable for a superconducting cable, that does not require a significant over-dimensioning of the conductor.

5. Fault and over currents in superconducting cable conductors

An important parameter in the design of a superconducting cable is whether it is able to withstand fault and over currents.

A superconducting cable conductor has a small cross sectional area compared to a conventional cable for the same rated current due to the larger current density in the superconducting material. Large fault currents, will mainly be running in the silver matrix. Because of this the apparent resistance of the conductor will be larger than the resistance of the conventional cable at high currents. This will give a large energy dissipation in the conductor and thus a rapid temperature rise. The cable has to be able to survive this temperature rise and within a short period of time be able to return to nominal current.

Methods for lowering the temperature rise in the superconducting conductor are currently evaluated in the Danish cable project, e.g. to shorten the time that the fault current runs in the conductor. A superconducting current limiter could be a solution to the problem.

6. Conclusion

Self and mutual inductances in a layered structure like the one present in a superconducting cable conductor have been studied theoretically.

Good agreement between theory and measurement is observed for the inter layer current distribution.

The latest cable conductor design yields a low conductor loss of 0.60 ±0.1 W/m·phase (2 kArms, 50 Hz, 77 K) which, to our knowledge, is the lowest value reported so far, for these high currents.

Fault and over currents are considered together with the overall design, construction and production of the superconducting power cable.

Acknowledgements

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