Analysis of AC Loss in Superconducting Power Devices Calculated From Short Sample Data

J. J. Rabbers, B. ten Haken, and H. H. J. ten Kate

***Abstract*—A method to calculate the AC loss of superconducting power devices from the measured AC loss of a short sample is developed. In coils and cables the magnetic field varies spatially. The position dependent field vector is calculated assuming a homogeneous current distribution. From this field profile and the transport current, the local AC loss is calculated. Integration over the conductor length yields the AC loss of the device. The total AC loss of the device is split up in different components. Magnetization loss, transport current loss and the loss due to the combined action of field and current all contribute to the AC loss of the device. Because ways to reduce the AC loss depend on the loss mechanism it is important to know the relative contribution of each component. The method is demonstrated on a prototype transformer coil wound from $Bi_2Sr_2Ca_2Cu_3O_x$/Ag superconducting tape. Differences between the model assumptions and devices are pointed out. Nevertheless, within the uncertainty margins the calculated AC loss is in agreement with the measured loss of the coil.**

***Index Terms*—AC loss, BSCCO/Ag tape, coils, electric power applications.**

I. INTRODUCTION

THE ELECTRIC power applications are an area where $Bi_2Sr_2Ca_2Cu_3O_x$/Ag tapes can be used at liquid nitrogen temperature. Several projects worldwide are running to build and investigate coils, transformers and power cables [1]–[5]. The AC loss of the superconductor in an electric power device is one of the factors that determines the efficiency of the device and the cost of the cooling machine. Therefore, design tools to evaluate the AC loss of a device beforehand and optimize the design to make optimal use of the expensive conductor are necessary.

In this paper a model to calculate the AC loss of electric power devices, based on the measured AC loss of a short sample and the magnetic field distribution in a device, is presented. Similar approaches can be found in [6] and [7]. The assumptions in the model are pointed out. Various components of the total AC loss of superconductors in devices where AC current and AC magnetic field are present simultaneously are distinguished. Their contribution to the AC loss of a device is evaluated, and implications for the reduction of the AC loss are discussed. The calculation method is illustrated on a prototype coil wound from $Bi_2Sr_2Ca_2Cu_3O_x$/Ag tape. The results are compared with the measured loss.

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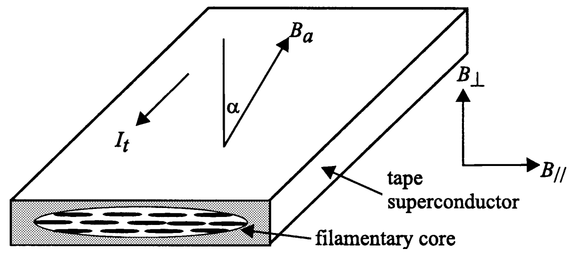

Fig. 1. Tape superconductor and the definitions of B_a, α, I_t and the directions $B_\perp$ and $B_{//}$.

II. MODEL

The AC loss of a conductor in an electric power device like a cable or a transformer coil depends on the transport current flowing through the conductor and the local magnetic field generated by the other conductors. The AC loss of the device is obtained from an integration of the loss along the length of the conductor:

$$P(I_t) = 2\int_0^{L/2} P_{tot}\left(B_a(l),\, \alpha(l),\, I_t\right)\, dl \tag{1}$$

in which $B_a(l)$ the magnetic field at position l along the length of the tape, $\alpha(l)$ the orientation of the magnetic field, I_t the transport current, L the total length of the conductor in the device and P_{tot} is the total AC loss of the superconductor. The definitions of B_a, $B_\perp$, $B_{//}$ and α for a tape conductor are shown in Fig. 1.

III. MAGNETIC FIELD PROFILE

The magnetic field in e.g., a coil varies spatially. In Fig. 2 the magnetic field components $B_\perp$ and $B_{//}$ in a two-layer model coil are shown (details of the coil in Section V). The magnetic field in the middle of the layer (radially), from the middle ($z = 0$) to the edge of the coil is calculated assuming uniform current distribution. In this coil ferromagnetic elements at the edges of the coil are used to shape the magnetic field and reduce the $B_\perp$-component of the magnetic field at the edges [8]–[10]. These field components give rise to much higher AC loss than axial magnetic field. The radial magnetic field in an air core coil and a coil with small ferromagnetic cores (c-cores) and small and large ferromagnetic cores (c and C-cores) [8] is shown in Fig. 2. The iron at the coil edges does not influence the axial magnetic field.

However, the current is flowing in the filamentary core of the tape, see Fig. 1, and not in a uniform layer, giving rise to extra magnetic field in the $\perp$-direction due to the spacing between the

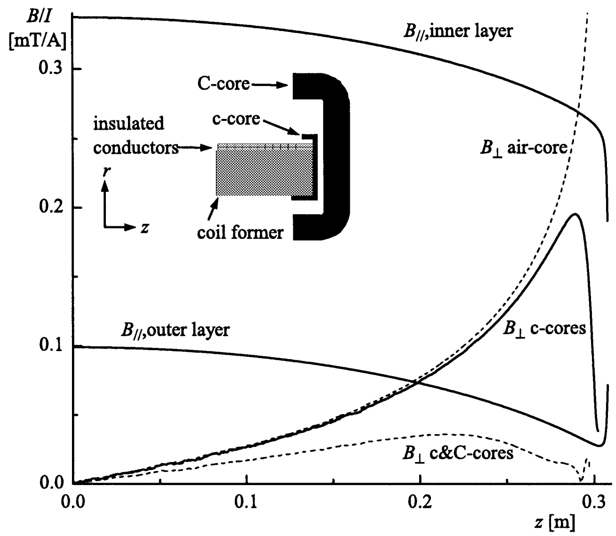

Fig. 2. Magnetic field as a function of the axial position ($z = 0$, midplane) in a coil with ferromagnetic elements to reduce the $B_\perp$ component. Coil edge with small and large ferromagnetic cores.

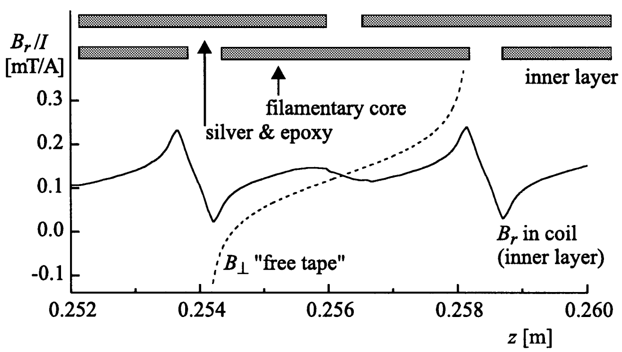

Fig. 3. Magnetic field detail, calculated in a model with separate filamentary cores. Comparison with field in a free tape (field of the tape plus the average of the field in the coil over one tape width).

cores of neighboring conductors. A typical example of the regular pattern that is the result of this is shown in Fig. 3 ($B_\perp$-component).

When the AC loss of a conductor in the device has to be calculated, the difference from the profile of a single tape without neighboring tapes should be accounted for, since this is the situation in AC loss experiments of single tapes and AC loss models for single tapes. The dotted line in Fig. 3 shows the $B_\perp$-component of a free tape carrying transport current (the average of the magnetic field in the coil over one tape width is added to the field of the free tape).

A complicating factor is that also screening currents are flowing in the conductor as well as the transport current. Here the magnetic field is calculated with only transport current in the conductor, neglecting screening currents. However when the transport current increases, screening currents are suppressed and transport current prevails. The field profile as calculated in Fig. 3 becomes more and more valid as the transport current increases.

The behavior of conductors with a spatially varying field over the cross section, other than the self-field, is not known yet.

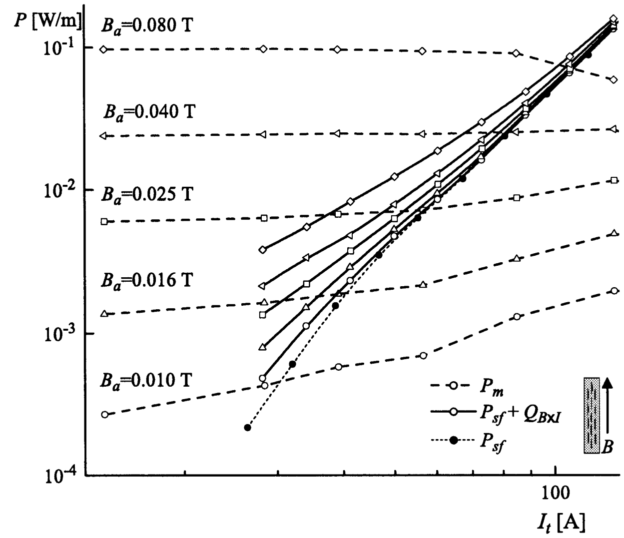

Fig. 4. AC loss components of a BSCCO/Ag tape conductor carrying AC transport current and exposed to AC magnetic field parallel to the wide face of the tape. The symbols represent measured points, the lines are guides to the eye. ($f = 48$ Hz, $T = 77$ K).

Time consuming numerical calculations taking into account all the factors mentioned above could be performed to obtain values for the AC loss of devices, but the possibility to calculate the consequences of design changes quickly is lost. The influence of the simplifications discussed above on the calculated loss of the model coil is evaluated in Section IV.

IV. AC Loss of a BSCCO/Ag Tape

In a transport cable or a coil a conductor is carrying an alternating transport current while it is exposed simultaneously to an alternating magnetic field. The AC loss under these conditions is already reported by several groups [11]–[13]. The total AC loss, $P_{tot}(B_a, \alpha, I_t)$ in (1), can be split up in different components [14]; magnetization loss (P_m), transport current loss (P_{sf}) and a component originating from the interaction of transport current and magnetic field ($P_{B\times I}$). An example is given in Fig. 4 [14]. The different components are plotted as a function of transport current for various magnetic field amplitudes. The sum of the components is the total AC loss.

The relative contribution of the three components to the AC loss of a device depends on the ratio between magnetic field and transport current and the orientation of the magnetic field. Field components perpendicular to the wide face of the tape conductor result in a P_m and $P_{B\times I}$ that is about one order of magnitude larger than when the field is parallel to the wide face of the tape conductor [14].

Because no analytical models are available to describe the total AC loss as a function of transport current and magnetic field with different orientations accurately for a wide range of field and currents, an engineering formula for the total AC loss $P_{tot}(B_a, I_t, \alpha) = P_m + P_{sf} + P_{B\times I}$ is developed [14]:

$$P_{tot}(B_a, I_t, \alpha) = \frac{C_1(\alpha)B_a^p \cdot C_2(\alpha)B_a}{C_1(\alpha)B_a^p + C_2(\alpha)B_a} + C_3 I_t^q + C_4(\alpha)B_a I_t^2. \quad (2)$$

TABLE I
PROPERTIES OF THE MODEL COIL

Tape length [m]	394
Inner/outer Ø [mm]	440/442
Height [mm]	614
Number of layers	2
Number of turns	273

The parameters $C_{1\ldots4}$ and p and q are determined by fitting (2) to measured total AC loss data [14]. The value of p and q is between 3 and 4. The way to reduce the AC loss of different components is different. Therefore it is necessary to distinguish the three components in AC loss of a device.

In order to be competitive with conventional conductors the AC loss of a superconductor should be sufficiently low. When only alternating transport current is flowing through a conductor that is not exposed to a magnetic field, the loss is at a minimum value (for devices working with AC). The loss of the conductor used in this paper is about 0.5 mW/Am at $I_t = 100$ A. Additional magnetic field, which is always present in devices increases the loss. A magnetic field parallel to the wide face of the conductor of the order of 0.1 T adds a comparable amount to the AC loss, a magnetic field perpendicular to the wide face of the tape of the order of 0.01 T also adds a comparable amount. A target for the AC loss of one tenth of the loss in a copper conductor, including the cooling penalty, is 0.5 mW/Am [15], which can at present only be reached in devices where the magnetic field is sufficiently low.

In the next section the field profiles and the engineering formula are used to calculate the loss of a model coil.

V. AC Loss of a Model Coil

In Table I the properties of the model coil are listed. The coil is part of a resonator coil system [16], and evaluated here separately to illustrate the calculation method. The field profiles of the coil are already shown in Fig. 2 for different magnetic configurations.

A. Small c-Cores

In Fig. 5 the measured and calculated loss of the model coil with small c-cores is shown. The AC loss of the coil, dotted line, is measured with a calorimetric method. The amount of nitrogen gas that flows out of the cryostat per unit time is a direct measure for the dissipation inside the cryostat. The uncertainty that is shown for the measurement is ± 1.3 W. This number is based on fluctuations in the signal on the timescale of the measurement.

The solid line displays the calculated AC loss of the coil. The loss is calculated with (1) The uncertainty in the calculated loss, $\pm 15\%$, is the uncertainty in the AC loss measurement of the tape conductor and the modeling of the loss with the engineering formula. Within the uncertainty margins, the calculated loss of the coil with small ferromagnetic elements (c-cores) is in agreement with the measured loss. Also the contribution of the components P_m, $P_{B\times I}$, P_{sf} to the loss of the coil are shown (broken lines). All components contribute significantly to the AC loss of the coil.

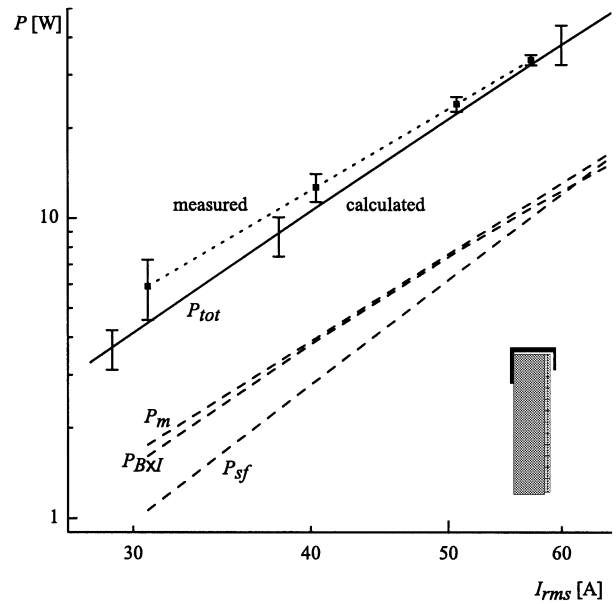

Fig. 5. Measured and calculated loss of the model coil with c-cores as a function of current through the coil. ($f = 48$ Hz, $T = 77$ K).

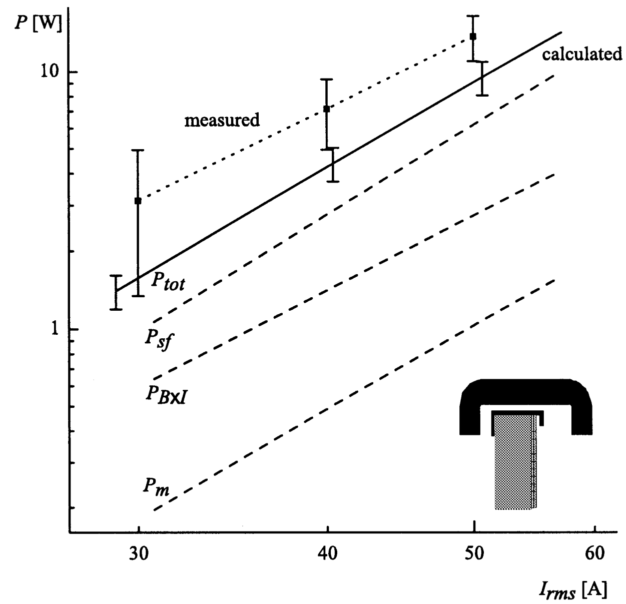

Fig. 6. Measured and calculated loss of the model coil with c and C-cores as a function of current through the coil. ($f = 48$ Hz, $T = 77$ K).

B. Small and Large c-Cores

When the perpendicular magnetic field at the edges of the coil is even further reduced the relative contribution of the loss components changes. In Fig. 6 the measured (dotted line) and calculated (solid line) loss of the coil with c and C-cores is shown. The magnetic field perpendicular to wide face of the tape is minimized in this coil, and the amplitude of the magnetic field is so low that the contribution of P_m and $P_{B\times I}$ are relatively low. The component P_{sf} is dominant. This is a situation that also occurs in power cables where the tapes are spiraled edge-to-edge around a former. Perpendicular field components are also minimal in that case. The parallel magnetic field component is relatively small.

VI. Discussion

It is important to know the contribution of the different components to the AC loss of a electric power device in order to decide which method has to be chosen to reduce the loss. The self-field loss contributes significantly to the AC loss of the coil with field shaping elements or power cables. Using conductors with twisted filaments will not reduce this component. The self-field loss component is reduced when the current carrying capacity of the conductor is not completely used, i.e., operating at e.g., half the critical current. The self-field loss is reduced almost one order of magnitude but twice the amount of expensive conductor is necessary. Another possibility is to use a cable with transposed strands instead of a tape with a very high critical current.

The magnetization loss (P_m) and the component originating from the interaction of magnetic field and transport current ($P_{B\times I}$), can be reduced, in principle. Conductors with many fine twisted filaments and possibly resistive barriers between the filaments have to be used. However, decoupling the filaments electromagnetically in BSCCO/Ag tape conductors is only demonstrated for magnetic field parallel to the wide face of the tape up to field amplitudes that are reached in coils (0.1 T). For magnetic field perpendicular to the wide face of the tape conductor, full decoupling is only observed for very small field amplitudes. High interfilamentary resistance and very small twist pitches are required in that case. This is difficult to achieve in the BSCCO/Ag conductors. A reduction of the $P_{B\times I}$ component in BSCCO/Ag conductors with twisted filaments is not reported yet. However the, related, dynamic resistance [17] in low-T_c conductors with decoupled filaments is lower than in conductors with coupled filaments [18].

In general, the strategy that has to be used to reduce the AC loss in electric power devices depends on the magnetic field profile in the device and the relative contribution of the different components to the AC loss.

VII. Conclusions

A method to calculate the AC loss of electric power devices is developed. The calculated loss of a model coil is in agreement with the measured loss within the uncertainty margin of $\pm 15\%$ for the calculation. The method uses the field profile in the device and the measured AC loss of a short sample to calculate the loss of the device.

In order to calculate the AC loss of a device in a straightforward way without time consuming numerical methods, several assumptions are necessary:

1) The magnetic field profile is calculated assuming a layer with uniform current distribution instead of separate filamentary cores. Screening currents are neglected.
2) The AC loss measured on a single tape is used to calculate the AC loss of the device. The different field gradient that is present in the coil is not taken into account.

Since the calculated loss is in agreement with the measured loss, the influence of the assumptions on the loss is not significant in the coils treated here.

The AC loss can be split up in different components. In transport cables the magnetic field is low and the transport current loss is dominant, and in large coils the magnetic field is high and the magnetization loss is dominant. Since the different components require different techniques to reduce them, it is necessary to know the relative contribution of the different components.

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