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Ac-loss measurement of coated conductors: The influence of the pick-up coil position

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ABSTRACT

The ac-loss measurement by the magnetization method requires calibration for obtaining absolute values. A convenient way of calibration is the calorimetric measurement which yields, within the measuring accuracy, absolute loss values. In the magnetization measurement the hysteresis loop of sample magnetization which determines the losses is measured via the integration of magnetic flux penetrating a pick-up coil. The ratio of flux integral to magnetization integral and hence the calibration factor is however, for a given pick-up coil geometry, not exactly a constant, but depends on the magnetization current pattern within the sample. Especially for thin tapes in perpendicular external field this effect has to be taken into consideration in order to avoid miss measurements. The relation between measured flux and sample magnetization was calculated for special cases of magnetization current distribution in the sample as a function of the pick-up coil position. Furthermore calibration factors were measured as a function of the ac-field amplitude and the result compared with available theoretical models. A good agreement was found between experiment and theory.

1. Introduction

Coated conductors, the second generation of high temperature superconducting tapes are the most promising candidates for ac-applications like transformers, motors, generators and magnets for fusion research. For these applications low ac-losses are required as a crucial precondition. Ac-losses are measured via the sample magnetization [1,2], by a calorimetric method [3,4] or by a combination of both [5,6].

The widely used ac-loss measuring technique by the magnetization method is based on the measurement of magnetic flux, created by the sample magnetization, with a pick-up coil wound around the sample. In general it is tactilely assumed that the hysteresis loop integral of magnetic flux penetrating the pick-up coil is proportional to the hysteresis loop integral of sample magnetization, which determines the losses. This is however only exact for the infinite slab. For finite sample geometries the ratio of measured flux to sample magnetization is not a constant, but depends, for a given pick-up coil position, on the magnetization current distribution within the sample. Especially for thin superconducting tapes (e.g. coated conductors) with a pick-up coil close to the sample in a perpendicular magnetic ac-field a significant error may be introduced into a loss measurement if this effect is not considered.

In this article the relation between measured flux and sample magnetization is calculated for special cases of magnetization current distribution as a function of the pick-up coil position. Furthermore the ratio of integrated flux to integrated sample magnetization is considered. From the measurement of ac-losses by the magnetization method and independently by a calorimetric method the dependence of the calibration factor as a function of the external ac-field amplitude is obtained. Comparison of the experimental results with available theoretical models shows a good agreement.

2. Ac-loss measurement

2.1. Magnetization measurement

The measurement of the magnetization loop of the sample, which is proportional to the dissipated energy per cycle, is the commonly used technique of loss measurement in an ac-field. In a multifilament superconductor the total sample magnetization is created by filament magnetization, coupling currents between filaments and eddy currents in the normal conducting matrix. In a monofilamentary superconductor or in a coated conductor with a single superconducting layer no coupling currents exist.

The principle of a standard magnetization measurement consists of a pickup coil wound around the sample and a second pick-up coil which compensates the voltage induced by the time

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varying external field. The signal of both coils connected in series, $\Delta U(t)$, is proportional to time derivative of the magnetic flux created by the sample magnetization. It is usually assumed that this flux is proportional to the sample magnetization. We discuss this point in detail later.

2.2. Calibration

The magnetization method is easy to perform and quick, but the measured voltage signal depends, at given losses per unit volume, not only on the geometry of sample and pickup coil, but also on the magnetization pattern within the sample. To get absolute loss values, calibration of the system is necessary. This can be done with a sample of known losses, but geometry and magnetization pattern of the test sample must be the same as those of the sample to be measured. This condition cannot always easily be fulfilled.

A way of a direct loss measurement is the calorimetric technique, which allows, at liquid helium temperature (4.2 K), sensitivities down to 10^{-8} W [4]. At liquid nitrogen temperature (77 K) the sensitivity of the calorimetric measurement is however much smaller and thermal time constants become rather long. A combination of a magnetization measurement with a calorimetric calibration at 77 K combines the advantages of both techniques, an easy and precise loss measurement by the magnetization method and an exact calibration by the less sensitive and more time consuming calorimetric method [5,6].

The measured signal $\Delta U(t)$ in the magnetization measurement is highest, if the pickup coil is close to the sample and the dimensions of its cross section are small compared to the smallest sample dimension. With respect to a high sensitivity of the measurement it is therefore advantageous to use a pickup coil wound closely around the sample. On the other hand a pickup coil with a sufficiently large distance from the sample yields a signal $\Delta U(t)$ that is not dependent on the magnetization pattern of the test sample.

2.3. The infinite slab

Let us first consider an infinite slab with the magnetic field parallel to the infinite dimension, see Fig. 1. The energy loss per unit volume and per cycle in a harmonic ac-field $B(t) = B_0 \sin \omega t$ is obtained by multiplying the measured compensated pickup voltage signal with $B(t)$, integrating over one cycle and dividing by the sample cross section $d \cdot L$ and by the number of pickup coil turns N [5]

$$Q_{\text{slab}} = \frac{1}{\mu_0 \, dLN} \int_0^{2\pi/\omega} B(t) \Delta U(t) \, dt. \tag{1}$$

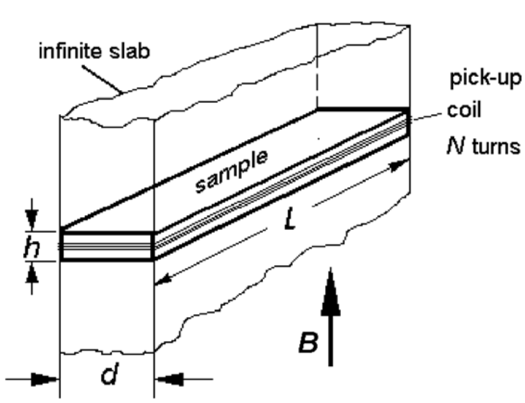

Fig. 1. Sample and pick-up coil geometry.

2.4. Sample of finite height

The measured pickup voltage $\Delta U(t)$ of a sample with a finite height h is, at given loss per unit volume, Q, by a factor of c smaller. To obtain the real losses, we therefore have to multiply the value calculated with Eq. (1) by c, i.e.

$$Q = c \cdot Q_{\text{slab}}. \tag{2}$$

The calibration factor c depends on the geometry of the pickup coil and on the sample dimension h in field direction. For a thin sample like that shown in Fig. 1, c can become very large. There is furthermore a dependence of c on the magnetization current distribution within the sample. This dependence is largest for a thin sample in perpendicular field, which will be discussed in the following.

3. Relation between magnetic flux and sample magnetization

Calculating the losses according to Eq. (1) one assumes that $\Delta U(t) = \mu_0 \, NdL \cdot dM/dt$, where M is the magnetization, i.e. the magnetic moment per unit volume, measured in units (A/m). This yields the area of the magnetization loop of $Q = \int B \, dM$.

The above assumption is however, for a sample of finite height h, an approximation, because the pickup coil does not measure the time derivative of the magnetic moment, but that of the compensated magnetic flux Φ in units (Vs) penetrating the pickup coil (the compensated magnetic flux is the flux created by the sample magnetization, i.e. the measured total flux minus flux created by the external magnetic field).

Replacing $\mu_0 dLM$ by Φ is the slab approach, where the total generated flux penetrates the pick-up coil. For a sample of finite height this procedure introduces an error, because part of the flux returns within the pick-up coil. The magnetization loop area (multiplied by $\mu_0 dL$) therefore differs from the hysteresis loop area of the magnetic flux. This error increases with decreasing sample height h and with decreasing distance between sample and pickup coil.

3.1. Calculation of the ratio magnetic flux to magnetic moment for a thin tape

For the purpose of a thin, nearly two-dimensional superconducting tape (the thickness of the superconducting layer in a coated conductor is in the micrometer range) in a perpendicular magnetic field it is useful to introduce the quantity magnetic moment per unit length of the tape, m/L, measured in (A/m). The ratio of the measured magnetic flux to the magnetic moment of the sample depends on the current distribution in the sample as well as on the geometry and position of the pickup coil. To illustrate this effect we calculate the relation between the magnetic moment caused by the magnetization currents in an ac-field and the magnetic flux penetrating a pickup coil as function of its position. We consider two cases of magnetization currents within the tape:

(1) A homogeneous current distribution in the tape, which is approximately achieved for full penetration of the ac-field under the assumption of a constant critical current density. A magnetization current I flows in one direction for $x > 0$, and in opposite direction for $x < 0$, see Fig. 2. The magnetic moment per unit length of the tape is

$$m/L = I \cdot d/4. \tag{3}$$

(2) The same magnetization current I is concentrated at the edges of the tape, it flows, at $x = \pm d/2$, in opposite directions on both sides. This simulates the case of small ac-field amplitudes where the field does not penetrate the superconducting tape. Here we have a magnetic moment per unit length of

$$m/L = I \cdot d. \tag{4}$$