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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Superconductivity –
Part 13: AC loss measurements – Magnetometer methods for hysteresis loss in superconducting multifilamentary composites

Supraconductivité –
Partie 13: Mesure des pertes en courant alternatif – Méthodes de mesure par magnétomètre des pertes par hystérésis dans les composites multifilamentaires supraconducteurs

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

SUPERCONDUCTIVITY –

Part 13: AC loss measurements – Magnetometer methods for hysteresis loss in superconducting multifilamentary composites

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 61788-13 has been prepared by IEC technical committee 90: Superconductivity.

This second edition cancels and replaces the first edition published in 2003. It constitutes a technical revision.

Modifications made to the second edition are

- to extend to the measurement of superconductors in general, in various sample sizes and shapes, and at temperatures other than 4,2 K,
- to use the word "uncertainty" for all quantitative (associated with a number) statistical expressions and eliminate the quantitative use of "precision" and "accuracy" in accordance with the decision at the June 2006 IEC/TC90 meeting in Kyoto.

The text of this standard is based on the following documents:

FDIS	Report on voting
90/302/FDIS	90/306/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 61788 series, under the general title: *Superconductivity*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

IEC Technical Committee 90 proposes magnetometer and pickup coil methods for measuring the AC losses of Cu/Nb-Ti composite superconducting wires in transverse time-varying magnetic fields. These represent initial steps in standardization of methods for measuring the various contributions to AC loss in transverse fields, the most frequently encountered configuration.

It was decided to split the initial proposal mentioned above into two documents covering two standard methods. One of them describes the magnetometer method for hysteresis loss and low frequency (or sweep rate) total AC loss measurement in a slowly varying magnetic field, and the other describes the pickup coil method for total AC loss measurement in higher frequency (or sweep rate) magnetic fields. The frequency range is 0 Hz – 0,06 Hz for the magnetometer method and 0,005 Hz – 60 Hz for the pickup-coil method. The overlap between 0,005 Hz and 0,06 Hz is a complementary frequency range for the two methods.

This standard deals with the magnetometer method.

SUPERCONDUCTIVITY –

Part 13: AC loss measurements – Magnetometer methods for hysteresis loss in superconducting multifilamentary composites

1 Scope

This part of IEC 61788 describes considerations for the measurement of hysteretic loss in Cu/Nb-Ti multifilamentary composites using DC- or low-ramp-rate magnetometry. This international standard specifies a method of the measurement of hysteretic loss in multifilamentary Cu/Nb-Ti composite conductors. Measurements are assumed to be on round wires with temperatures at or near 4,2 K. DC or low-ramp-rate magnetometry will be performed using either a superconducting quantum interference device (SQUID magnetometer, See Annex A.) or a vibrating-sample magnetometer (VSM). In case differences between the calibrated magnetometer results are noted, the VSM results, extrapolated to zero ramp rate, will be taken as definitive. Extension to the measurement of superconductors in general is given in Annex B.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at <http://www.electropedia.org)

IEC 61788-5, *Superconductivity – Part 5: Matrix to superconductor volume ratio measurement – Copper to superconductor volume ratio of Cu/Nb-Ti composite superconductors*

3 Terms and definitions

For the purposes of this part of IEC 61788, the terms and definitions given in IEC 60050-815, together with the following terms and definitions, apply.

3.1
AC loss
P
power dissipated in a composite superconductor due to application of a time-varying magnetic field or electric current

Note 1 to entry: The AC loss per magnetic field cycle is designated *Q*. Although all such loss is inevitably "hysteretic" in the general sense, the AC loss in a superconducting composite is assumed to be separable into "hysteresis-", "eddy-current-", and "coupling-" loss components, as defined below (see Note 1 and Note 2 of IEC 60050-815:2000, 815-04-54).

[SOURCE: IEC 60050-815:2000, 815-04-54, modified – The original two notes have been replaced by a new note to entry.]

3.2
hysteresis loss

P_h

loss of the type whose value per cycle is independent of frequency arising in a superconductor under a varying magnetic field

Note 1 to entry: This loss is caused by the irreversible magnetic properties of the superconducting material due to pinning of flux lines.

Note 2 to entry: Hysteresis loss is that which takes place only within the superconducting regions of the Cu/Nb-Ti composite, and hence which would be present even in the absence of the matrix. The hysteresis loss per cycle, designated Q_h, is associated with the area of the magnetization vs. field (M-H) hysteresis loop; the associated M is occasionally referred to as the "persistent-current magnetization".

[SOURCE: IEC 60050-815:2000, 815-04-55, modified – A new note to entry has been added.]

3.3
eddy current loss

P_e

loss arising in the normal matrix of a superconductor or the structural material when exposed to a varying magnetic field, either from an applied field or from a self-field

Note 1 to entry: The eddy current loss per cycle is designated Q_e.

[SOURCE: IEC 60050-815:2000, 815-04-56, modified – A new note to entry has been added.]

3.4
coupling loss

P_c

loss arising in multi-filamentary superconducting wires with a normal matrix due to coupling current

Note 1 to entry: The coupling loss per cycle is designated Q_c.

[SOURCE: IEC 60050-815:2000, 815-04-59, modified – A new note to entry has been added.]

3.5
proximity effect coupling loss

P_{pe}

loss stemming from currents that circulate along the filaments of a superconducting composite and across the intervening matrix rendered superconducting by proximity effect (PE)

Note 1 to entry: By so doing, the PE currents compete for the same paths as the coupling currents. Since the PE entire current path is superconductive, P_{pe} is a persistent-current effect and when it is present serves to augment P_h. Proximity effect can be expected in Cu/NbTi composites when the interfilamentary spacing drops below about 1 µm. The PE loss per cycle is designated Q_{pe}.

3.6
demagnetization

phenomenon in which the specimen's magnetization reduces the applied magnetic field sensed by the superconductor

Note 1 to entry: It depends on the strength of that magnetization as well as sample geometry and applied field orientation. It is usually negligible for multifilamentary Cu/Nb-Ti composites at 4,2 K in large magnetic fields.

3.7
flux creep

thermally activated flux motion in which fluxons move from one pinning centre to another

Note 1 to entry: Flux creep refers to the logarithmic time dependence of decay (at fixed applied field strength and sample temperature) of a superconductor's persistent-current magnetization. A significant level of flux creep will contribute a frequency dependence to the hysteretic loss. The effect is negligible for Cu/Nb-Ti composites, except when proximity effect coupling is present.

[SOURCE: IEC 60050-815:2000, 815-03-20, modified – The original note has been replaced by a new note to entry.]

3.8
flux jump
cooperative and transitional movements of pinned fluxons as a result of a magnetic instability initiated by mechanical, thermal, or electrical disturbances

Note 1 to entry: A flux jump manifests itself as a sudden drop in magnetization of the superconductor.

3.9
filamentary volume
total volume of the filaments within a given sample

3.10
composite volume
total specimen volume including both superconductor and matrix

3.11
sweep amplitude
H_{max}
maximum value of the applied field

3.12
magnetization loop
trace of specimen magnetization as function of applied magnetic field strength as the field is varied around a complete cycle starting and ending at $+H_{max}$

Note 1 to entry: The area of the loop, Q, is the "energy loss per cycle". As indicated above, by analogy with the components of power dissipation, Q can be regarded as having the components Q_h, Q_e, Q_c, *and* Q_{pe}.

4 General specifications

4.1 Target uncertainty

The target uncertainty of this method is defined as coefficient of variation (COV; standard deviation divided by the average). The COV shall not exceed 5 %.

Important variables and elements affecting the uncertainty of the results are specified as follows. Introduction to the uncertainty is given in Annex C.

4.2 Uncertainty and uniformity of the applied field

An applied magnetic field system shall provide the magnetic field with a relative standard uncertainty not to exceed 0,5 %. The applied field shall have a uniformity of 0,1 % over the volume of the specimen.

4.3 VSM calibration

The goal of VSM calibration is to ensure that the specimen's moment is measured with a relative combined standard uncertainty not to exceed 1 %. Calibration shall be performed with all cryostats and any other metal parts in place (as they would be in an actual measurement).

The magnetometer shall be calibrated using a small Ni sphere whose calibration is traceable to the National Institute of Standards and Technology (N.I.S.T., U.S.A.)'s standard reference material 772a. This is a Ni sphere 2,383 mm in diameter prepared from high purity Ni wire.

The certified value of its magnetic moment, *m*, is (3,47 ± 0,01) mA m^2 at 298 K, in a field, *H*, of 398 kA/m ($\mu_0 H$ = 0,5 T). In calibration against this sphere, field and temperature corrections are made according to

$$m = 3{,}47\,[1 + 0{,}0026\,\ln(H/398)][1 - 0{,}00047(T - 298)] \qquad (\text{mA m}^2)$$

with *H* in kA/m (1 kA/m = 12,56 Oe) and *T* in K. For convenience, a calibration field of about 400 kA/m is recommended.

4.4 Temperature

Measurements shall be made at or near 4,2 K, the normal boiling point of liquid helium and the actual temperature of measurement reported to a combined standard uncertainty not exceeding 0,05 K.

At temperatures other than 4,2 K, the temperature shall be known with a relative standard uncertainty not exceeding 1,2 %, which corresponds to the above combined standard uncertainty at 4,2 K.

4.5 Specimen length

Several magnetization components are functions of specimen length, *L*. Length dependence needs to be eliminated or appropriately allowed for.

a) In relatively short samples, critical current density anisotropy in the longitudinal and transverse directions will lead to a measurable "end effect" and hence to a length dependence in Q_h. To avert this possibility, specimens shall be prepared whose superconducting components (filaments) have a length/diameter ratio of more than 20.

b) Proximity effect can be expected to be present in Cu/Nb-Ti multifilamentary composites only if the filament spacing, d_s, is less than about 1 µm. Under this condition, the resulting PE contribution to magnetization will depend on sample length, *L*, and twist pitch, L_p. Under this condition, these lengths will need to be taken into account in the following way when reporting the results:

   - for $d_s <$ about 1 µm and the filaments are untwisted, Q_h shall be measured as function of *L* and the results extrapolated to zero *L*;
   - for $d_s <$ about 1 µm and the filaments are twisted, Q_h shall be measured at $L > 5\,L_p$.

4.6 Specimen orientation and demagnetization effects

Loss measurements shall be made on strand specimens in a transverse magnetic field. For the fully penetrated fine filaments of a multifilamentary Cu/Nb-Ti strand, demagnetization is negligible. By the same token, it is negligible for round-, flat-, or square-cross-sectioned bundles of such strands. However, for the sake of completeness in reporting the results, the specimen configuration shall be reported.

4.7 Normalization volume

It may be desirable to report hysteretic loss in terms of the superconductor volume. To pursue this route, it is necessary to invoke a standard procedure for determining the matrix (Cu)/superconductor volume ratio (see IEC 61788-5). For the purposes of this standard, these steps are eliminated, and AC loss is to be reported in terms of total composite volume. Volume should be measured with a relative combined standard uncertainty not to exceed 0,5 %.

4.8 Mode of field cycling or sweeping

The applied field may be changed *point-by-point* over the field cycle starting and ending at H_{max}. SQUID magnetometry is restricted to this mode of field change, and it is optional for the VSM to be operated in point-by-point mode. The VSM may also be operated semicontinuously, the *M-H* loop being constructed from 200 or so (*M,H*) data-pairs.

5 The VSM method of measurement

5.1 General

For a full description of the application of VSM technique, the paper by Collings et al. [1[1]] is recommended.

5.2 VSM measurement principle

The basic principle of the Foner [2] VSM is as follows. The specimen to be measured is located in a uniform magnetic field, which causes it to become magnetized. The specimen is mechanically oscillated near a set of pickup coils. The oscillating magnetic moment causes an oscillation in the magnetic field linking the pickup coils, thereby inducing an AC voltage which is then detected and converted into a magnetic moment value by electronic circuitry. The magnetometer is a "substitution" rather than "absolute" device and its output signal requires calibration against a reference. Custom-made (hand-made) VSMs do exist, but increasingly, commercial versions of this machine are used. In general, they share the following characteristics. The specimen to be measured is typically mounted on a vertical rod which vibrates longitudinally (vertically) with a position amplitude of about 1 mm and at a suitably low frequency.

The magnetic field may be supplied by either a horizontally mounted iron-core electromagnet (EM) or a vertically mounted superconducting solenoid (SCS) – the conventional attitudes in each case – causing the vibration direction of the sample to be perpendicular or parallel, respectively, to the field direction. The pickup coils are appropriately located and connected in pairs such that any external field oscillations (magnetic noise) are cancelled and only the specimen-generated field oscillations are detected. A typical experimental setup of VSM measurement is given in Figure 1.

The loss is determined from the numerically integrated area of the full *M*-*H* loop.

The specimen is positioned at the "sweet spot", a small region of the pickup coil space within which the detected signal changes only slightly with variation of vertical or horizontal positioning of the specimen. Using a small calibrating specimen of, for example Ni, the specimen space is to be explored and the sweet spot determined as the volume within which the response does not change more than 2 %. Suppose Z to be the vertical direction, Y the direction along the magnet-pole axis, and X the direction normal to the magnet-pole axis, then the center of the sweet spot is located by a procedure known as "saddling", viz seeking the maximum signal along Z combined with the maximum along X and the minimum along Y.

5.3 VSM specimen preparation

The size of the sweet spot in the typical VSM restricts specimen volume to less than about 30 mm^3. For the VSM measurement of Cu/Nb-Ti multifilamentary composite wires, it is permissible to use one of three alternative specimen configurations as shown in Figure 2.

a) Short straight specimen: This consists of one or more straight pieces of strand (the size of the bundle depending on the signal strength required) up to about 1 cm in length. The ends of the strand pieces are to be finely ground flat (see for example [1]).

b) Multiturn coil: If long lengths of fine wire are to be measured, they may be wound for measurement into a multiturn coil (see for example [3]). For EM-VSM measurement, the coil may be oval in shape and mounted with its long axis vertically (parallel to the vibration axis). The plane of the coil will be normal to the field direction. For SCS-VSM measurement, the multiturn coil should be round and mounted with its plane perpendicular to the vibration axis.

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[1] Numbers in square brackets refer to the Bibliography.

To minimize the possibility of interstrand coupling, the strands of the short straight bundle and the multiturn coil are to be insulated by varnish, or by potting, or otherwise be electrically separated.

c) Helical coil: Lying between the short straight sample and the multiturn coil is the helical coil. As recommended by Goldfarb et al. [4], this consists of a single length of strand wound along the grooves of a screw thread. The axis of the helix is parallel to the field direction which can then be regarded as transverse to the specimen axis if the pitch angle is less than 8°. Using the helical technique, a relatively long piece of moderately thick strand can be accommodated for measurement.

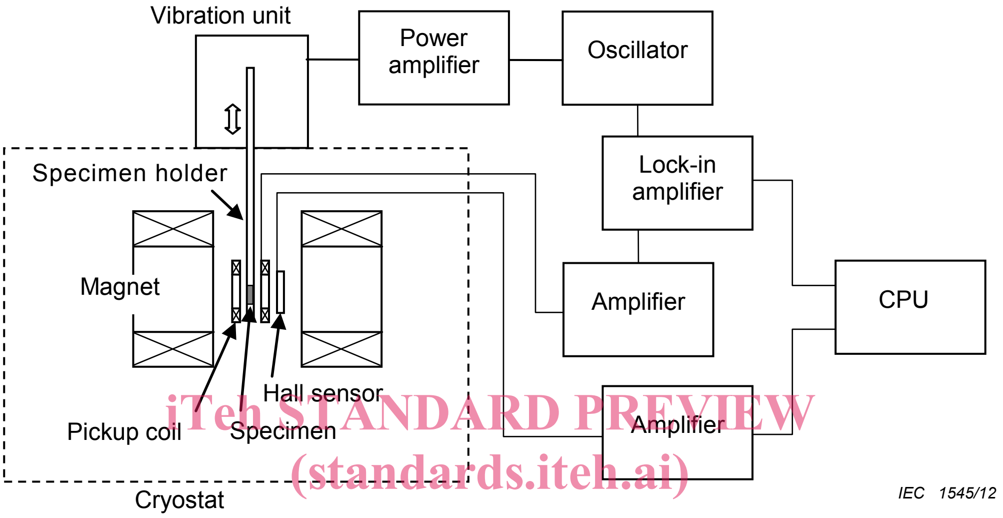
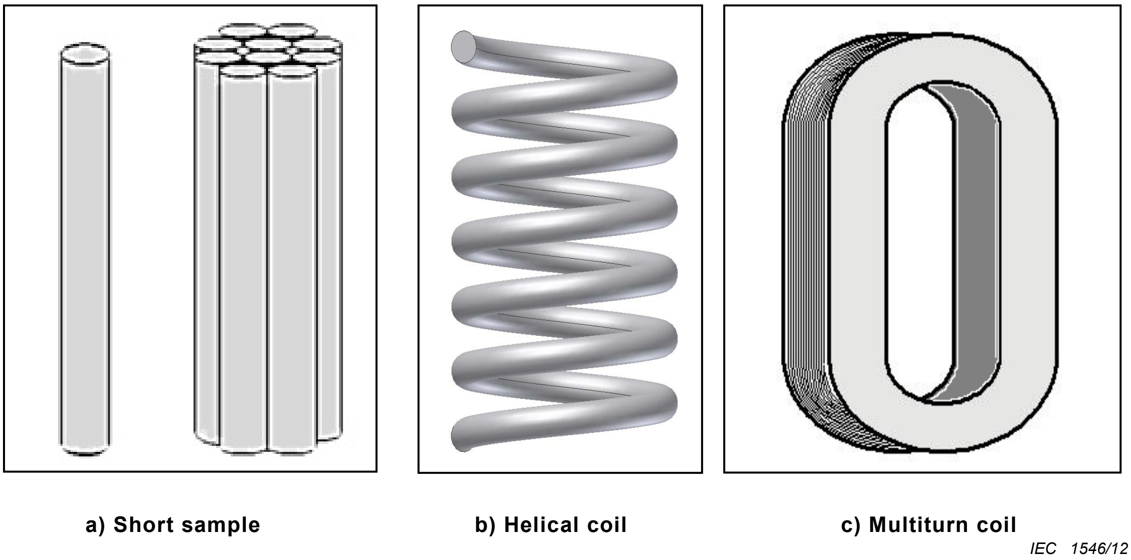


Figure 1 – A typical experimental setup of VSM measurement


a) Short sample

b) Helical coil

c) Multiturn coil

Figure 2 – Three alternative specimen configurations for the VSM measurement

5.4 VSM measurement conditions and calibration

5.4.1 Field amplitude

The measuring field amplitude, to be determined by the application, shall be specified (see Clause 6).

5.4.2 Direction of applied field

The field shall be applied transversely to the strand axis. Thus, the applied field will be normal to the axis of the short straight specimen, normal to the plane of the multiturn coil, or parallel to the axis of the helical coil.

5.4.3 Rate of change of the applied field (sweep rate)

5.4.3.1 Effect of coupling

The sweep rate of the applied field should be sufficiently low as to render negligible any coupling contribution, P_c, to the AC loss. But in very low sweep rate, including point-by-point measurement, the effect of strong coupling will re-appear in the form of eddy current decay (exponential creep), the effect of which will then need to be taken into account. If detectable coupling is encountered in measurements made at typical VSM sweep rates, Q_h shall be determined by extrapolation to zero $\mathrm{d}H/\mathrm{d}t$, it having been previously determined that the Q measured is linear in $\mathrm{d}H/\mathrm{d}t$. For specimens with a low n value in the voltage-current relation at higher temperatures, Q_h shall be also determined by a similar extrapolation.

5.4.3.2 Proximity effect

In fine filament composites the measurer shall be alert to the possibility of a proximity effect (PE) contribution to the hysteretic loss. The PE contribution enhances the hysteretic loss beyond that expected for (a bundle of) individual filaments. It is a valid contribution to the total hysteric loss and should therefore be included.

5.4.3.3 Flux jump

In thick filament composite the measurer shall be also alert to the possibility of a flux jump, which disturbs to measure the intrinsic magnetization. The report shall include a note on flux jump (6.3 d)).

5.4.4 Waveform of the field change

The field sweep rate shall be linear between the end-points $\pm H_{\max}$, see 3.11 and 4.7 above.

5.4.5 Specimen size and shape correction

Calibration shall be performed as directed above under 4.2. Furthermore, consideration shall be given to the size and shape of the specimen with respect to those of the calibration sample.

The specimen shall be centered on the sweet spot.

For specimens smaller than the calibration sample, no size correction need be applied.

For specimens larger than the calibration sample, one of two size corrections are allowed:

a) a replica of the specimen will be fabricated from Ni and used as a secondary standard;

b) the sweet spot will be mapped out and a size and shape correction will be generated based on the measured response.

5.4.6 Allowance for addendum (background subtraction)

The measurer shall be alert to the possibility that the specimen holder and associated parts (for example temperature sensor) may make a significant contribution to the loss. Whenever this turns out to be the case, a correction shall be applied.

5.4.7 Data point density

In modern computer-controlled VSM measurements, it is possible to select, from a broad range, the number of data-pairs that make up the *M-H* loop. If fine structure is present (for example those describing the various features of PE magnetization), a high point density is necessary. If point-by-point measurements are made, the *M-H* loop shall consist of no less than 100 data pairs.

6 Test report

6.1 General

The report of the results of the AC loss testing shall include at least the following specifications. The reason for any missing information shall be explained.

6.2 Initiation of the test

- Name of the laboratory performing the test
- Names of groups or persons requesting the test
- Other details concerning sponsorship of the test

6.3 Technical details

a) The superconducting composite strand – details when available
   - Manufacturer and strand identification code
   - Strand materials
   - Strand design, for example number of re-stacks
   - Cu/superconductor volume ratio within filamentary bundle and overall
   - Matrix residual resistance ratio, *RRR*
   - Twist pitch
   - Filament count
   - Filament diameter

b) The specimen – the strand as prepared for measurement
   - Form of the specimen (bundle or coil)
     - Dimensions of bundle, number of wires in bundle
     - Length of the bundle
   - Dimensions of coil
   - Total length of strand in sample
   - Sample mounting – orientation with respect to the applied field

c) Test facilities – apparatus and conditions
   - Magnetometer calibration procedure and related details
   - Uncertainty of field determination and calibration procedure
   - Uncertainty of temperature determination and procedure used