IEC 61788-8

Edition 2.0 2010-06

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Superconductivity –
Part 8: AC loss measurements – Total AC loss measurement of round superconducting wires exposed to a transverse alternating magnetic field at liquid helium temperature by a pickup coil method

Supraconductivité –
Partie 8 : Mesure des pertes en courant alternatif – Mesure de la perte totale en courant alternatif des fils supraconducteurs ronds exposés à un champ magnétique alternatif transverse par une méthode par bobines de détection

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**Part 8: AC loss measurements –
Total AC loss measurement of round
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FOREWORD

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International Standard IEC 61788-8 has been prepared by IEC technical committee 90: Superconductivity.

This bilingual version (2014-03) corresponds to the monolingual English version, published in 2010-06.

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

The main changes with respect to the previous edition are listed below:

– extending the applications of the pickup coil method to the a.c. loss measurements in metallic and oxide superconducting wires with a round cross section at liquid helium temperature,
– u1 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
90/243/FDIS	90/249/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.

The French version of this standard has not been voted upon.

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- withdrawn,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

Magnetometer and pickup coil methods are proposed for measuring the AC losses of 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, 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 to 0,06 Hz for the magnetometer method and 0,005 Hz to 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 covers the pickup coil method. The test method for standardization of AC loss covered in this standard is partly based on the Versailles Project on Advanced Materials and Standards (VAMAS) pre-standardization work on the AC loss of Nb-Ti composite superconductors [1][1)].

1) Numbers in square brackets refer to the bibliography.

SUPERCONDUCTIVITY –

Part 8: AC loss measurements – Total AC loss measurement of round superconducting wires exposed to a transverse alternating magnetic field at liquid helium temperature by a pickup coil method

1 Scope

This part of IEC 61788 specifies the measurement method of total AC losses by the pickup coil method in composite superconducting wires exposed to a transverse alternating magnetic field. The losses may contain hysteresis, coupling and eddy current losses. The standard method to measure only the hysteresis loss in DC or low-sweep-rate magnetic field is specified in IEC 61788-13 [2].

In metallic and oxide round superconducting wires expected to be mainly used for pulsed coil and AC coil applications, AC loss is generated by the application of time-varying magnetic field and/or current. The contribution of the magnetic field to the AC loss is predominant in usual electromagnetic configurations of the coil applications. For the superconducting wires exposed to a transverse alternating magnetic field, the present method can be generally used in measurements of the total AC loss in a wide range of frequency up to the commercial level, 50/60 Hz, at liquid helium temperature. For the superconducting wires with fine filaments, the AC loss measured with the present method can be divided into the hysteresis loss in the individual filaments, the coupling loss among the filaments and the eddy current loss in the normal conducting parts. In cases where the wires do not have a thick outer normal conducting sheath, the main components are the hysteresis loss and the coupling loss by estimating the former part as an extrapolated level of the AC loss per cycle to zero frequency in the region of lower frequency, where the coupling loss per cycle is proportional to the frequency.

2 Normative references

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

IEC 60050-815:2000, *International Electrotechnical Vocabulary (IEV) – Part 815: Superconductivity*

3 Terms and definitions

For the purposes of this document, the following terms and definitions, as well as those of IEC 60050-815, apply.

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

[IEC 60050-815:2000, 815-04-54]

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

[IEC 60050-815:2000, 815-04-55]

3.3
eddy current loss
***P*e**
loss arising in the normal conducting matrix of a composite superconductor or the structural material when exposed to a varying magnetic field, either from an applied field or from a self-field

[IEC 60050-815:2000, 815-04-56, modified]

3.4
(filament) coupling (current) loss
***P*c**
loss arising in multi-filamentary superconducting wires with a normal matrix due to coupling current

[IEC 60050-815:2000, 815-04-59]

3.5
(filament)coupling time constant
τ
characteristic time constant of coupling current directed perpendicularly to filaments within a strand for low frequencies

[IEC 60050-815:2000, 815-04-60]

3.6
shielding current
current induced by an external magnetic field applied to a superconductor and which includes coupling current and eddy current after a field change in composite superconductors

3.7
critical (magnetic) field strength
***H*c**
magnetic field strength corresponding to the superconducting condensation energy at zero magnetic field strength

[IEC 60050-815:2000, 815-01-21]

3.8
magnetization (of a superconductor)
magnetic moment divided by the volume of the superconductor

NOTE The macroscopic magnetic moment is also equal to the product of the shielding current and the area of the closed path in a composite superconductor together with the magnetic moment of any penetrated trapped flux.

3.9
magnetization method for AC loss
method to determine the AC loss of materials from the area of the loop of the magnetization curve

NOTE When pickup coils are used to measure the change in flux, which is then integrated to get the magnetization of stationary coiled specimens, the method is called the pickup coil method.

[IEC 60050-815:2000, 815-08-15, modified]

3.10
pickup coil method
method to determine the AC loss of materials by evaluating electromagnetic power flow into the materials by pickup coils

NOTE The pickup coil arrangement consists essentially of a primary winding (a superconducting magnet supplied with a time varying current) and a pair of secondary windings (pickup coils), one of which (the main pickup coil) contains the specimen to be measured and the other (the compensation coil) plays two roles: 1) it compensates the signal from the main pickup coil when empty; 2) it supplies the field sweep information.

Here the coaxial and concentric arrangement of the pickup coils as shown in Figure 1 is used as the standard one for the AC loss measurement. In order to obtain sufficient volume of the wire specimen to be measured and at the same time to expose it to a transverse magnetic field, it must be wound into a coil. The specimen so prepared is also referred to as the "coiled specimen".

3.11
background loss
apparent loss obtained by the pickup coil method in the case where no specimen is located inside the pickup coils

NOTE The background loss gives the experimental error in the system of the AC loss measurement by the pickup coil method. It results from phase shift of electrical signal in the compensation process, an additional magnetic moment induced in many components of experimental hardware, and external noise. The background loss can be reduced by adjusting the experimental setup and compensated by subtracting it from measured AC loss as shown in 7.4.2.

3.12
effective cross-sectional area of the coiled specimen
total specimen volume divided by the larger of the specimen coil height or the pickup coil height

3.13
bending strain
ε_b
strain in percent arising from pure bending defined as $\varepsilon_b = 100\ r\ /\ R$, where r is a half of the specimen thickness and R is the bending radius

[IEC 60050-815:2000, 815-08-03]

NOTE In the pickup coil method, the coiled specimen by react and wind technique is prepared with an attention to the permissive level of bending strain.

3.14
***n*-value (of a superconductor)**
n
exponent obtained in a specific range of electric field strength or resistivity when the voltage current $U(I)$ curve is approximated by the equation $U \propto I^n$

[IEC 60050-815:2000, 815-03-10]

4 Principle

The test consists of applying an alternating transverse magnetic field to a specimen and detecting the magnetic moment of shielding currents induced in the specimen by means of pickup coils for the purpose of estimating the AC losses defined in 3.1.

5 Apparatus

5.1 Testing apparatus

The testing apparatus shall be constructed such that the pickup coils and a coiled specimen are arranged in a uniform alternating magnetic field applied by a superconducting magnet.

The coils of the testing apparatus are arranged as described below. Typically, the main pickup and compensation coils are coaxially positioned on the outside and inside of the coiled specimen, respectively.

The applied alternating magnetic field shall have a high uniformity as shown in 7.1.5.

The testing apparatus has a sub-system that calculates the magnetization and the AC loss of the specimen by integrating the signal of the pickup coils. A typical electrical circuit for the AC loss measurement is given in Figure 2.

5.2 Pickup coils

Pickup coils shall be made of very fine insulated wire, such as insulated copper wire with a diameter of 0,1 mm, to avoid eddy currents at low temperatures.

The pickup coil formers shall be made of non-metallic and non-magnetic material such as glass fiber reinforced plastic, phenol resin, etc.

The main pickup coil shall be arranged coaxially and adjusted concentrically outside the compensation coil. The standard arrangement is shown schematically in Figure 1, where the height of the compensation coil is the same as that of the main pickup coil. The number of turns in the compensation coil shall be usually adjusted to be a little larger than the balance level in which the total interlinkage flux of the applied magnetic field into the compensation coil is equal to that into the main pickup coil.

The pickup coil system shall be constructed so that the coiled specimen can be taken in and out easily from the system.

The pickup coil method has geometrical errors in relation with the arrangement of the coiled specimen and the pickup coils. The geometrical error is mentioned briefly in Annex C. To achieve a low uncertainty due to geometrical effects of less than 1 %, the following arrangement for the coiled specimen and the two pickup coils shall be the standard one; a height of 30 mm for the coiled specimen, a height of 10 mm for the pickup coils, a coil radius of 18 mm for the specimen, and a 2 mm difference between the radii of the specimen and each pickup coil. In the case where the arrangement of the specimen and pickup coils are a little different from the above standard one, the geometrical error in the arrangement shall be estimated, as shown in Annex C. If the geometrical error cannot be estimated quantitatively, the calibration indicated in Annex D may need to be performed.

5.3 Compensation circuit

The total interlinkage flux of the applied field in the compensation coil is usually a little larger than that in the main pickup coil by adjusting the number of turns. The signal from the main pickup coil is counterbalanced against a reduced signal of the compensation coil by means of the compensation circuit. For delicate adjustment of the reduction ratio, called the compensation coefficient, the compensation circuit usually has the structure of a resistive potential divider with a wide adjustable range of four or five digits, namely minimum adjustable unit of 1 part in 10^4 or 1 part in 10^5. The delicate adjustment using the wide range of the circuit results in a full compensation to almost remove the tilt in the magnetization loop in accordance with the procedures in 7.4.1. The number of digits for the compensation circuit is designed with the condition that the minimum adjustable unit is sufficiently fine in comparison with the ratio of the moment-related component to the field-related one in the signal from the main pickup coil.

6 Specimen preparation

6.1 Coiled specimen

6.1.1 Winding of specimen

A coil former shall be used to wind the specimen into a single-layer solenoidal coil. When the specimen has an insulation layer, the turns of the coil shall be tightly wound right next to adjacent turns. When the specimen surface is not coated with an insulating material, the specimen shall be wound with an equal space between turns by inserting a non-metallic and non-magnetic spacer such as a fishing line to achieve turn-to-turn insulation of the specimen. The diameter of the spacer shall be approximately half the specimen diameter. In the cases where demagnetization effects due to the adjacent turns ought to be reduced, the specimen shall be also wound by inserting an appropriate spacer between the turns.

6.1.2 Configuration of coiled specimen

The coil height of the specimen shall be more than three times as high as that of the pickup coil in order to reduce geometrical error coming from the end effects of the coiled specimen.

6.1.3 Maximum bending strain

The coiled specimen of each superconducting wire shall be prepared and arranged between the two concentric pickup coils with considering permissive tolerance of bending strain. For specimens of Nb-Ti wires, the maximum bending strain shall not exceed a permissive level for the DC critical current measurement.

NOTE For the DC critical current measurement of Nb-Ti composite superconductors, the permissive level of 3 % is given in IEC 61788-1 (2006) [3].

6.1.4 Treatment of terminal cross section of specimen

Both ends of a specimen shall be opened and ground by emery paper of 12 μm (800 mesh) to 7 μm (1 000 mesh) to prevent filaments from contacting each other.

6.2 Specimen coil form

The former upon which the specimen is wound shall be made of non-metallic and non-magnetic material such as glass fiber reinforced plastic and phenol resin. An adhesive, such as cyanoacrylate or epoxy resin, shall be used as a bonding material to bond the specimen to the coil former to keep the cylindrical coil shape.

7 Testing conditions

7.1 External applied magnetic field

7.1.1 Amplitude of applied field

The standard condition for the amplitude of applied field shall be ranged from around 0,1 T to 1 T by considering the frequency range to evaluate the coupling time constant.

NOTE In the past round-robin tests, the measurement amplitude of applied field was 1 T in the range from 0,005 Hz to 1 Hz for Cu/Nb-Ti multifilamentary wires and 0,5 T from 0,005 Hz to 10 Hz for three-component superconducting wires, as represented in A.2.

7.1.2 Direction of applied field

In a coiled specimen, the external field shall be applied along the coil axis.

7.1.3 Waveform of applied field

The standard waveform of the applied field shall be a sine waveform or a triangular waveform.

7.1.4 Frequency of applied field

The present method shall be used in the range of frequency up to the commercial levels of 50 Hz and 60 Hz to measure the total AC loss. In the region of higher frequency, attentions shall be paid to reduce electromagnetic noise from metallic parts in the vicinity of the pickup coils as shown in Annex A.

For the superconducting wires with fine filaments, the number of measurement points shall be more than five in an extensive range of frequency on a logarithmic scale so as to calculate the coupling time constant from linear frequency dependence of the coupling loss as shown in 8.6. In the measurement of frequency dependence of AC losses, the amplitude of the applied field shall be fixed.

NOTE The linear frequency dependence of the coupling loss is observed in the range of lower frequency and smaller amplitude of applied magnetic field [4]. In cases where the coupling loss is not linearly dependent upon the frequency at a level of fixed amplitude, the range of measurement frequency shall be shifted to the lower side to obtain the linearity. Recommended ranges of the frequency are given in A.2 for Cu/Nb-Ti multifilamentary wires and three-component superconducting wires.

7.1.5 Uniformity of applied field

The applied field shall have uniformity within 5 % over the coil length of the specimen and within 1 % over the length of the pickup coils.

7.2 Setting of the specimen

The coiled specimen shall be arranged coaxially and concentrically between a main pickup coil and a compensation coil.

7.3 Measurement temperature

The specimen and the pickup coils shall be immersed in liquid helium. The measurement temperature shall be determined using a calibrated thermometer or an atmospheric pressure measurement.

7.4 Test procedure

7.4.1 Compensation

The first step of the compensation is to measure a hysteresis loop of magnetization of the specimen for a fixed amplitude of applied field by subtracting the signal of the compensation coil from that of the main pickup coil as they are. Since the total interlinkage flux of the applied field into the compensation coil is a little larger than that into the main pickup coil, the obtained magnetization loop is usually tilted against the horizontal axis of applied magnetic field.

In the second step of the compensation, the signal from the compensation coil is loosely modified by multiplying by a compensation coefficient slightly less than unity through the compensation circuit to reduce the tilt of magnetization loop.

In the final step, the compensation coefficient is delicately adjusted to get the condition that both branches of the magnetization curve in increasing and decreasing processes are symmetric with respect to the horizontal axis in the regions around the extreme values of applied field.

7.4.2 Measurement of background loss

In order to estimate background loss in the pickup coil system including pickup coils, compensation circuit, amplifiers, etc., apparent loss shall be measured when no specimen is located inside the pickup coils. The measurement procedure is the same as that for usual specimens mentioned in 7.4.3.

7.4.3 Loss measurement

In the pickup coil method, the AC loss shall be calculated by integrating the product between the compensated signal from the main pickup coil (moment related) and the signal from the compensation coil (field related), following Equation (3). If the apparent background loss cannot be neglected in the system of loss measurement, the AC loss for the specimen shall be obtained by subtracting the background loss from the apparent, measured one. In the correction by the background loss, attention shall be paid to the sign of the background loss.

The AC loss can be also estimated by integrating the magnetization for the applied field over a period, as shown in Annex B.

7.4.4 Calibration

In general, calibration is a basic procedure in the AC loss measurement with imperfect detection of signals. A recommended method of the calibration is given in Annex D. On the other hand, if the conditions for the configuration of the pickup coils and the coiled specimen, indicated in Clauses 5 and 6 and Annex C are satisfied, the AC loss and magnetization measurements with an error due to the geometrical configuration less than a few percent can be performed without calibration. However, when the configuration of the pickup coil system is outside the given conditions, the calibration indicated in Annex D may need to be performed.

8 Calculation of results

8.1 Amplitude of applied magnetic field

The applied field $H_e(t)$ shall be calculated by substituting the measured voltage $U_c(t)$ from the compensation coil into Equation (1):

$$H_e(t) = \frac{1}{\mu_0 N_c S_c} \int_0^t U_c(t')\, d t' \tag{1}$$

where N_c and S_c are the number of turns and the interlinkage area per turn of the compensation coil, respectively. The initial time of integration is a zero-crossing point of $U_c(t)$. The zero level of the magnetic field is equal to the midpoint between the maximum and minimum levels of $H_e(t)$ in Equation (1). The amplitude shall be obtained as a half of difference between the maximum and minimum values of $H_e(t)$.

8.2 Magnetization

The magnetization shall be calculated by substituting the compensated voltage $U_{p\text{-}c}(t)$ from the pickup coils into Equation (2):

$$M(t) = \frac{1}{\mu_0 N_p S_s} \int_0^t U_{p\text{-}c}(t')\, \mathrm{d}t' \tag{2}$$

where N_p is the number of turns for the main pickup coil and S_s is an effective cross-sectional area of the coiled specimen obtained from dividing the total specimen volume by the height of coiled specimen. The initial time of integration is also the zero-crossing point of $U_c(t)$. The zero level of the magnetization is equal to the midpoint between the maximum and minimum levels of $M(t)$ in Equation (2).