BS EN 61788-8:2010

BSI Standards Publication

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

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National foreword

This British Standard is the UK implementation of EN 61788-8:2010. It is identical to IEC 61788-8:2010. It supersedes BS EN 61788-8:2003 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee L/-/90, L/-/90 Super Conductivity.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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Compliance with a British Standard cannot confer immunity from legal obligations.

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English version

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 (IEC 61788-8:2010)

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
(CEI 61788-8:2010)

Supraleitfähigkeit -
Teil 8: Messung der Wechselstromverluste -
Messung der Gesamtwechselstromverluste von runden Supraleiterdrähten in transversalen magnetischen Wechselfeldern mit Hilfe eines Pickupspulenverfahrens bei der Temperatur von flüssigem Helium
(IEC 61788-8:2010)

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CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
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Foreword

The text of document 90/243/FDIS, future edition 2 of IEC 61788-8, prepared by IEC TC 90, Superconductivity, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61788-8 on 2010-10-01.

This European Standard supersedes EN 61788-8:2003.

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.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN and CENELEC shall not be held responsible for identifying any or all such patent rights.

The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2011-07-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2013-10-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 61788-8:2010 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

[2] IEC 61788-13:2003	NOTE	Harmonized as EN 61788-13:2003 (not modified).
[3] IEC 61788-1:2006	NOTE	Harmonized as EN 61788-1:2007 (not modified).
[9] IEC 61788-2	NOTE	Harmonized as EN 61788-2.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050-815	2000	International Electrotechnical Vocabulary (IEV) - Part 815: Superconductivity	-	-

CONTENTS

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):

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

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):

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

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).

8.3 Magnetization curve

Over a period of the applied magnetic field from the initial time, the hysteretic magnetization curve can be obtained by plotting the magnetization versus the applied field. The zero levels of the magnetization and the applied field can be obtained as shown in 8.1 and 8.2.

8.4 AC loss

As shown in Annex B, the AC loss per cycle in a superconducting wire can be estimated by integrating Poynting's vector $\boldsymbol{E} \times \boldsymbol{H}$ on a closed surface surrounding the wire over a period T of alternating electromagnetic environment. In this case, the AC loss per unit volume P [W/m^3] shall be calculated by substituting the compensated voltage $U_{\text{p-c}}$ from the main pickup coil and the applied magnetic field H_e into Equation (3),

$$P = -\frac{f}{N_p S_s} \int_0^T U_{\text{p-c}}(t) H_e(t)\, dt \tag{3}$$

where f is the frequency of the applied magnetic field and equal to $1/T$. Under steady periodic conditions, Equation (3) is equivalent to the alternative expression of integrating the manetization defined by Equation (2) over a cycle of the applied field, as shown in Annex B.

In cases where eddy current loss in normal metal of the specimen is a minor component, the AC loss can be classified into two main components, hysteresis loss P_h and coupling loss P_c, by measuring the frequency dependence for a fixed amplitude of the applied magnetic field.

If the background loss cannot be neglected in the loss measurement system, the AC loss shall be obtained by subtracting the background loss from the measured value.

8.5 Hysteresis loss

The hysteresis loss in unit volume of the individual filaments, P_h, shall be obtained as an extrapolated level of the AC loss in unit volume at $f = 0$. The level can be extrapolated in the frequency dependence of AC loss per cycle by using linear regression.

NOTE In the measurements where the AC losses are not divided into the hysteresis loss and the coupling loss, for example in cases of specimens with low n-values, the results only of the total AC losses are reported.

8.6 Coupling loss and coupling time constant [5,6]

The coupling loss among the filaments shall be obtained by subtracting the hysteresis loss from the total AC loss in the region of lower frequency where the coupling loss per cycle estimated is proportional to the frequency. For isotropic superconducting round wires with fine filaments in a sine waveform of the applied magnetic field, the coupling loss in unit volume, P_c, is theoretically predicted by

$$P_c = 4\pi^2 \tau \mu_0 H_m^2 f^2 \tag{4}$$

where τ is the coupling time constant and H_m is the amplitude of applied magnetic field. The coupling time constant can be calculated from the proportional coefficient of the coupling loss per cycle to the frequency. The expressions of the coupling loss in the round wire for various types of waveforms of the applied field are given in Annex E.

9 Uncertainty

9.1 General

Background for introducing uncertainty, the definition and the application to the pickup coil method are summarized in Annex F and Annex G. The results of the relative combined standard uncertainties evaluated in Annex G are 3,8 % for the hysteresis loss and 5,4 % (5,5 %) for the coupling loss (the coupling time constant) as a typical example for NbTi conductors under the condition that the ratio of the hysteresis loss to the total AC loss is 0,5 on an average at the upper limit in the measurement frequency region. The target relative combined standard uncertainty of this method is defined as an expanded uncertainty with a coverage factor *k* of 2, which does not exceed 7,6 % and 10,8 % (11,0 %) respectively in the above example.

9.2 Uncertainty of measurement apparatus

Measurement apparatus with relative standard uncertainty not to exceed 0,5 % shall be used. The dimension measuring apparatus shall have a relative standard uncertainty not to exceed 0,5 %.

9.3 Uncertainty of 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 given in 7.1.5.

9.4 Uncertainty of measurement temperature

A cryostat shall provide the necessary environment for measuring AC loss and the specimen shall be measured while immersed in liquid helium. The specimen temperature is assumed to be the same as the temperature of the liquid. The liquid temperature shall be reported with a standard uncertainty not to exceed 0,05 K. For converting the observed atmospheric pressure in the cryostat to a temperature value, the phase diagram of helium shall be used. The atmospheric pressure measurement shall have low enough uncertainty to obtain the required uncertainty of the temperature measurement. For liquid helium depths greater than 1 m, a head correction may be necessary.

10 Test report

10.1 Identification of specimen

The specimen shall be identified, if possible, by the following:

a) name of manufacturer;
b) classification;
c) lot number;
d) matrix material;
e) dimension of the wire;
f) filament diameter;
g) number of filaments;
h) interfilamentary spacing;
i) copper / non-Cu ratio;
j) twist pitch;
k) residual resistance ratio (RRR);
l) thickness of insulation layer.

10.2 Configuration of coiled specimen

The following configuration of the coiled specimen shall be reported:

a) inner diameter;
b) outer diameter;

c) height;

d) number of turns;

e) effective cross-sectional area of coiled specimen;

f) volume ratio of coiled specimen volume within the height of the pickup coils to the volume of the space between the pickup coils.

10.3 Testing conditions

The following testing conditions shall be reported:

a) amplitude of applied field;

b) waveform of applied field;

c) frequency of applied field;

d) uniformities of applied field over the coil length of the specimen and the length of pickup coils;

e) measurement temperature;

f) measurement method of temperature;

g) sampling time of induced voltage of pickup coils;

h) magnitude of background loss.

10.4 Results

The following results shall be reported. In repeated measurements of the total AC loss, the hysteresis loss and the coupling loss (the coupling time constant), the average value and the relative expanded uncertainty for the coverage factor k of 2 shall be reported with the repeated number of times n:

a) total AC loss including a hysteresis loss and a coupling loss;

b) hysteresis loss;

c) coupling time constant or coupling loss;

d) magnetization curve.

In the measurements where the AC losses are not divided into the hysteresis loss and the coupling loss, the results only of a) and d) shall be reported.

It is recommended that the following results be reported, even in the case where controllable errors, such as the geometrical error of the pickup coil system mentioned in 5.2 and Annex C, can be reduced:

e) hysteresis loss and magnetization curve of the Pb standard specimen;

f) maximum and minimum values of magnetization value in Pb standard specimen under external magnetic field with the amplitude of 0,1 T;

g) critical field strength of Pb standard specimen.

10.5 Measurement apparatus

The test report shall contain the following information.

10.5.1 Pickup coils

a) Relation of the position between pickup coils and a coiled specimen

b) Parameters of main pickup coil (inner diameter, outer diameter, height, number of turns, wire material and diameter, material of coil form)

c) Parameters of compensation coil (inner diameter, outer diameter, height, number of turns, wire material and diameter, material of coil form)

10.5.2 Measurement system

a) Electrical circuit of measurement system

b) Material of cryostat

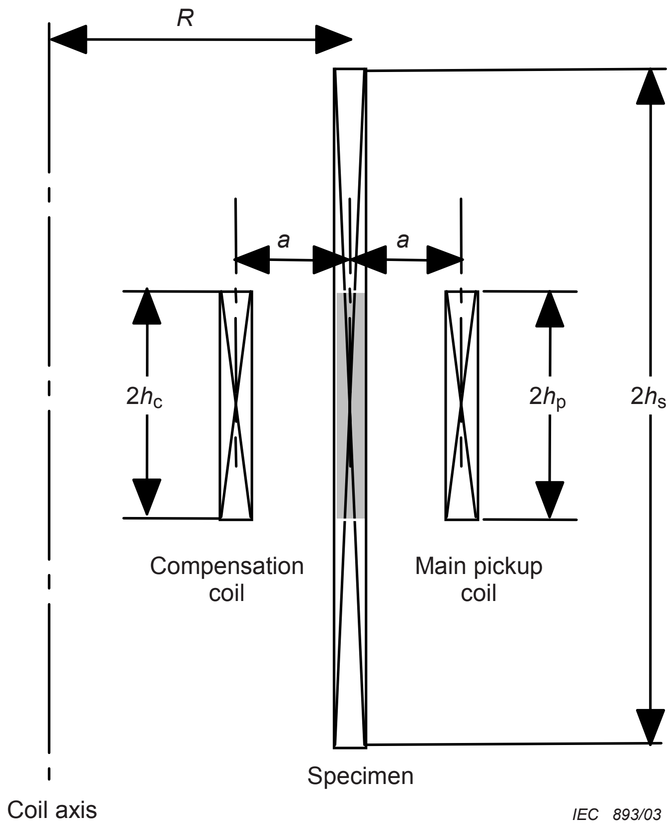

Figure 1 – Standard arrangement of the specimen and pickup coils

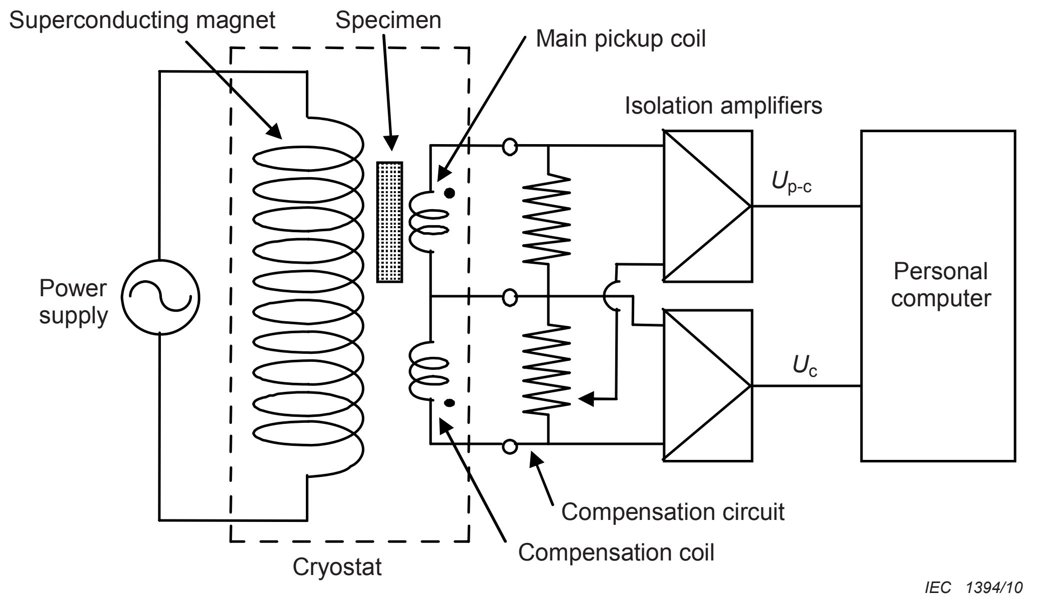

Figure 2 – A typical electrical circuit for AC loss measurement by pickup coils

Annex A
(informative)

Additional information relating to Clauses 1 to 10

A.1 Concerning the Scope

In general, the present pickup coil method is applicable to measure the total AC loss of the superconducting wires in the form of the coiled specimen indicated in 6.1 in wide ranges of the frequency and the amplitude of the applied magnetic field at liquid helium temperature. The upper limit of the frequency given in 7.1.4 is the maximum frequency that was used in the round-robin tests for the measurement of AC losses in Cu/Nb-Ti multifilamentary wires and three-component superconducting wires. The AC losses in the superconducting wires can be also measured with this method in a range of higher frequency with further attention to be paid to reduce electromagnetic noise due to eddy current generated in metallic parts in the vicinity of the pickup coils including super-insulation layers in the non-metallic cryostat and shielding current induced in the winding of the magnet for the applied magnetic field.

The present pickup coil method is applicable not only to the Cu/Nb-Ti multifilamentary wires and the three-component superconducting wires, but also extended in principle to other round superconducting wires indicated in the following under the condition that the method of calibration for the AC loss measurement in 7.4.4 and Annex D can be used:

a) the low-temperature compound superconducting wires of Nb_3Sn, Nb_3Al and so on;
b) the intermediate-temperature superconducting wires such as MgB_2;
c) the high-temperature superconducting wires of Bi-2212 and so on.

A.2 Coupling time constant

In the multifilamentary superconducting wires, the filaments are twisted to reduce the coupling loss in a transverse AC magnetic field. For the commercial metallic superconducting wires, the twist pitch is designed to restrict the coupling loss to a comparable level to the hysteresis loss of the individual filaments within the mechanical tolerance to the twisting in practical ranges of the frequency and the amplitude of applied magnetic field.

In the region of linear frequency dependence of the coupling loss per cycle, the coupling time constant can be calculated from the proportional coefficient of the coupling loss per cycle to the frequency at the fixed amplitude as shown in 8.6. In order to reduce an uncertainty in the evaluation of the coupling time constant, the measurement points shall be extended in a wide range of frequency on a logarithmic scale, where the hysteresis loss is predominant in the AC loss at the measurement point with the lowest frequency and the hysteresis loss and the coupling loss are comparable to each other at the measurement point with the highest. In the past round-robin tests, for example, the measurement frequency was in the range from 0,005 Hz to 1 Hz at the amplitude of magnetic field, 1 T, for Cu/Nb-Ti multifilamentary wires [7] and from 0,005 Hz to 10 Hz at 0,5 T for three-component superconducting wires [8].

A.3 Preparation of coiled specimen

The coiled specimen of each superconducting wire shall be prepared and arranged between the two concentric pickup coils while paying attention to permissive tolerance of bending strain. The permissive level shall be estimated from the conditions for the mechanical strain in the critical current measurement. For thicker wires, the conditions for the bending strain results in a larger radius of the coiled specimen. The geometrical error for the large specimens can be also estimated by considering the coefficient G indicated in Annex C. In the case where the permissive radius of the coiled specimen is out of the range given in Figure C.1, a similar set of sizes for the coiled specimen and pickup coils to the given examples shall be used. For a coiled specimen prepared by a wind-and-react method, on the other hand, the radius can be adjusted before the reaction heat treatment in the same manner as indicated in IEC 61788-2 [9] for the critical current measurement of Nb_3Sn superconducting wires. Electrical insulation between neighbouring turns in the coiled specimen shall be also ensured.

A.4 Cryogenic compensation method

An alternative for the compensation of the inductive voltage of the pickup coil as shown in Figure 2, is a compensation inside the cryostat. In this compensation scheme, the pickup coil and compensation coil are connected in anti-series directly in the cold without bringing the full signals out of the cryostat to room temperature and feed them to amplifiers.

The winding numbers of the pickup and compensation coils should be matched so that the remaining inductive signal of the coils connected in anti-series is minimised. Because the compensation will never be 'perfect', some fine tuning is necessary. Fine tuning can be performed with an inductive signal that is derived from the magnet current or with the signal from a small compensation coil inside the magnet. This fine tuning is performed at room temperature with amplifiers, similar to the compensation method described in 7.4 and shown in Figure 2.

The advantage of the cryogenic compensation method is that not the full voltage of the pick-up and compensation coils is brought up to room temperature and fed through the amplifiers. A difference in phase shift of the signal in the two amplifiers leads to an increase of the background loss (loss without sample in the pick-up coils) because a part of the inductive signal will appear as (in-phase) AC loss signal. Also disturbances of the signals in the wiring between the pickup and compensation coils and the amplifiers at room temperature which are not identical in both the pickup coil and compensation coil circuit can lead to an increase of the background loss. With the cryogenic compensation method the largest part of the compensation is performed in the cold. No large inductive signals are fed to amplifiers with possible difference in phase shift and the risk of disturbances of the signals between cryogenic temperature and room temperature is minimised. With the cryogenic compensation method the empty coil effect can be minimised and the sensitivity of the measurement can be improved.

Annex B
(informative)

Explanation of AC loss measurement with Poynting's vector [10]

In general, AC loss per cycle in a superconducting wire can be estimated by integrating Poynting's vector $\boldsymbol{E} \times \boldsymbol{H}$ on a closed surface A surrounding the wire over a periodic electromagnetic environment. The AC loss in unit volume of the specimen is given by

$$P = -\frac{f}{V_s} \int_0^T \mathrm{d}t \int_A \mathrm{d}\boldsymbol{A} \cdot \boldsymbol{E} \times \boldsymbol{H} \qquad \text{(B.1)}$$

where E and H are electric field and magnetic field on the surface A and V_s is a volume of the specimen surrounded by the surface A. When the specimen is exposed to a uniform alternating magnetic field H_e, the AC loss can be measured by pickup coils in the following way. In arrangements of the specimen and the pickup coils shown in Figure 1, for example, Equation (B.1) is changed into

$$P = -\frac{f\,d_p}{V_s} \int_0^T \mathrm{d}t\, H_e \int_\Gamma \mathrm{d}s\, E = -\frac{f}{n_p V_s} \int_0^T \mathrm{d}t\, H_e U_{p\text{-}c} \qquad \text{(B.2)}$$

where d_p is an average pitch of the pickup coil winding, n_p is the number of turns per unit length for the main pickup coil, and Γ is a path along the winding in a layer. In this way, the AC loss can be estimated by integrating the product between the applied magnetic field H_e and the compensated terminal voltage $U_{p\text{-}c}$ from pickup coils over the period. In Figure 1, the portion of the specimen surrounded by the closed surface is indicated by shadow. By substituting the magnetization M defined by Equation (2), Equation (B.2) leads to

$$P = \mu_0 f \int_0^T H_e \frac{\partial M}{\partial t} \mathrm{d}t = \mu_0 f \oint H_e \mathrm{d}M \qquad \text{(B.3)}$$

Under steadily periodic condition in which the magnetization curve per period is closed, Equation (B.3) can be changed into

$$P = -\mu_0 f \oint M \mathrm{d}H_e \qquad \text{(B.4)}$$

Geometrical error from the configuration of the specimen and pickup coils results from an approximation of the surface A by means of a side surface of the pickup coil. The quantitative consideration is presented in Annex C.

Annex C
(informative)

Estimation of geometrical error in the pickup coil method

The pickup coil method has geometrical error, as suggested in Annex B, due to imperfect detection by means of the pickup coils. If an apparent magnetization *M* obtained from Equation (2) is equal to $G(h_p, h_c, h_s, R, a)\,M_0$, Equation (B.4) leads to the following expression

$$P = -\mu_0\, f\, G(h_p, h_c, h_s, R, a) \oint M_0\, dH_e \quad \text{(C.1)}$$

where M_0 is an actual magnetization induced in the specimen. A coefficient *G* gives the geometrical error and is dependent only upon a height $2h_p$ of the main pickup coil, a height $2h_c$ of the compensation coil and a coil height $2h_s$ of the coiled specimen, a radius *R* of the coiled specimen and a difference *a* between the radii of the specimen and each pickup coil [11]. It is possible to measure AC losses fairly accurately when the coefficient *G* approaches unity.

According to this estimation of the geometrical error, we obtain the condition $|G - 1{,}00| < 0{,}01$ in the standard arrangement of the coiled specimen and pickup coils given in 5.2. Figure C.1 also shows the geometrical error for the case where the arrangement is a little different from the standard one.

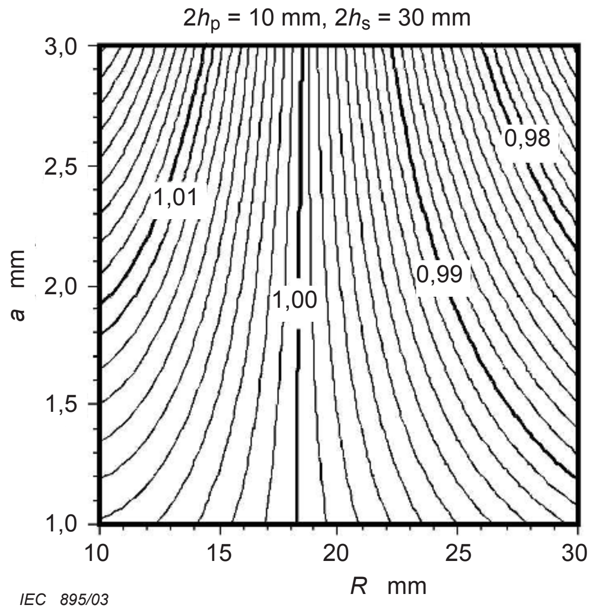

Figure C.1a – Example 1

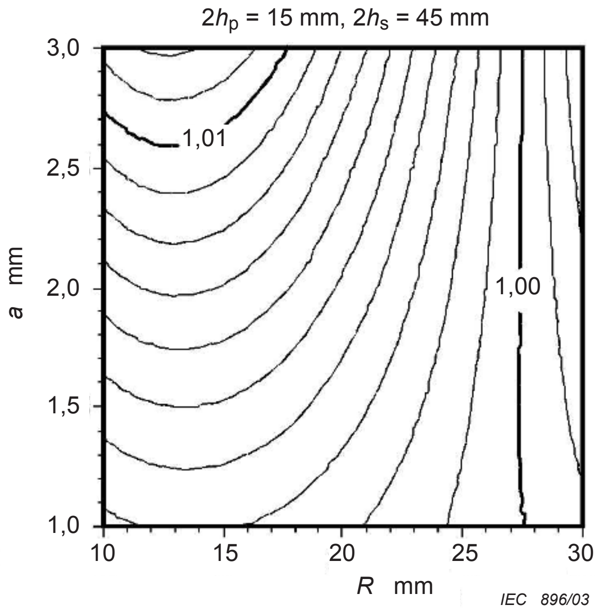

Figure C.1b – Example 2

Figure C.1 – Examples of calculated contour line map of the coefficient *G*

Annex D
(informative)

Recommended method for calibration of magnetization and AC loss

D.1 Outline of calibration

Calibration of magnetization is recommended to compensate for an incomplete measurement of time variation in induced magnetic moment in the specimen even in the case where controllable errors such as geometrical error of the pickup coil system mentioned in Annex C can be reduced. A standard specimen of a type I superconductor such as a high purity Pb wire shall be used for the calibration of magnetization. The magnetization can be calibrated by using the peak value of the reversible $M - H_e$ curve as shown in D.4. The procedure of the magnetization measurement for the standard specimen is in principle the same as that for the usual specimen wire except for the coil configuration and testing condition in the following.

D.2 Coil configuration of standard specimen

The standard specimen shall be co-wound loosely with a non-metallic and non-magnetic wire such as a fishing line for turn-to-turn insulation in a single layer coil. It is recommended that the diameter of the spacer be approximately one half of the specimen wire diameter.

Both ends of the standard specimen shall be opened. The condition of the coil height for the standard specimen is the same as that for the usual specimen.

D.3 Testing conditions of standard specimen

When the standard specimen is Pb, the amplitude of the applied field shall be 0,1 T. The waveform of the applied field shall be sine waveform and the frequency is in the range from 0,006 Hz to 0,06 Hz. A triangular waveform may be also used as the waveform of the applied field.

D.4 Calibration with magnetization of standard specimen

It is well known that the slope of the magnetization curve measured on a type-I superconductor with finite demagnetization depends on the magnitude of the demagnetization factor, but that the maximum magnetization is always the same and equal to the critical magnetic field strength H_c. This is confirmed by the experimental results obtained by SQUID magnetometry as shown in Figure D.1a. If the rounding of the curves is approximated by linear extrapolation, the experimental peak values are always the same and equal to the critical field strength of 39,8 kA/m with an error of 5 %, in excellent agreement with the directly measured field strength where the magnetization disappears.

Two sets of experimental results for the pure Pb wire using the pickup coil method are also given in Figure D.1b. In this figure, the solid and dashed lines indicate the results for frequencies of 0,006 Hz and 0,06 Hz, respectively. The pickup coils and the specimen were set under the conditions given in this standard. The magnetization curves have hysteresis dependent upon frequency. In the above range of frequency, the increasing-field branch is reproducible, whereas the decreasing-field branch is very sensitive to frequency [12]. As indicated by an arrow in the figure, if the peak level of magnetization is estimated in the increasing process, the level of 43,8 kA/m is equal to the critical field strength 42,2 kA/m plus or minus a few percent. The ratio of the predicted level of the peak to the measured one is a calibration coefficient for the measurements of magnetization and AC loss by the pickup coil system. Under the conditions for the pickup coil system indicated in the present standard, the AC loss measurement with an error less than a few percent can be performed without calibration.

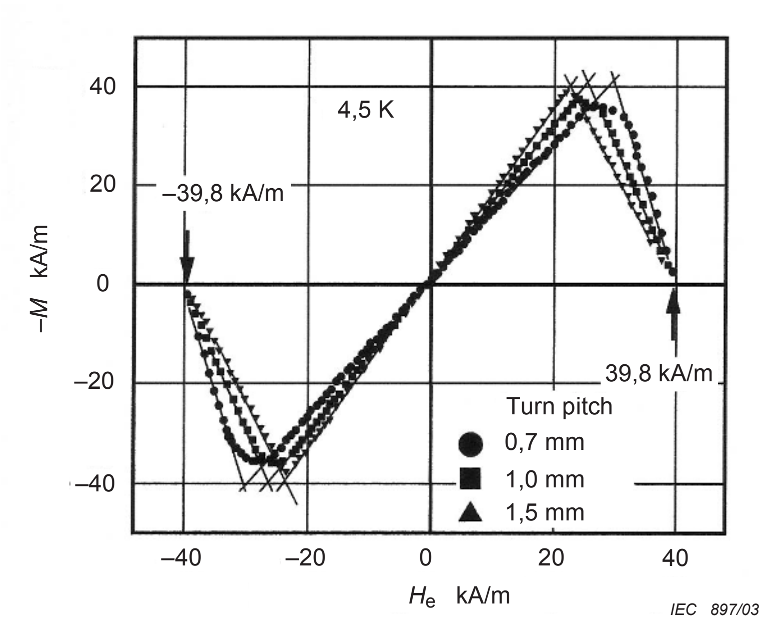

Figure D.1a – Magnetization curves of standard specimen of pure Pb (SQUID magnetometer)

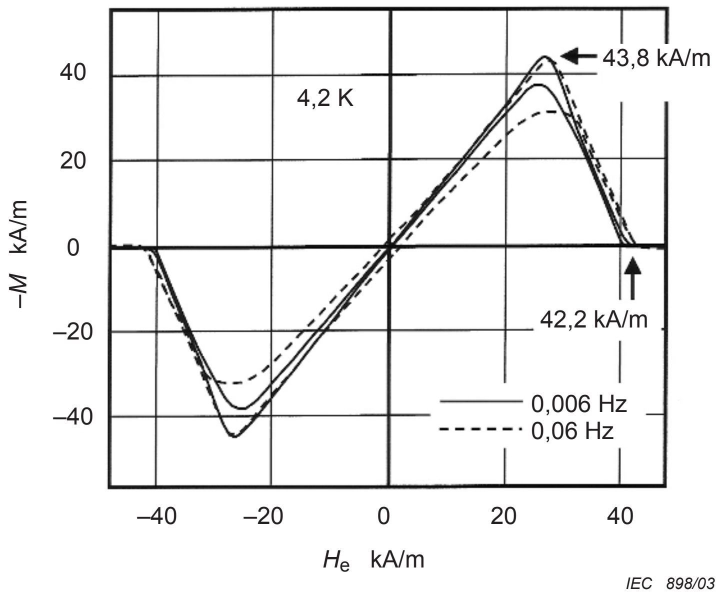

Figure D.1b – Magnetization curve of standard specimen of pure Pb (pickup coil)

Figure D.1 – Evaluation of critical field from magnetization curves

Annex E
(informative)

Coupling loss for various types of applied magnetic field

Under the electromagnetic conditions mentioned in 8.6 for isotropic superconducting wires with fine filaments, the expressions of the coupling loss for two types of applied field are given in the following:

$$P_c = 4\,\pi^2 \tau \mu_0 H_m^2 f^2 \text{ for sine waves} \tag{E.1}$$

$$P_c = 64\,\tau \mu_0 H_m^2 f^2 \text{ for triangle waves} \tag{E.2}$$

Specific parameters for each type of waveform are indicated in Figure E.1.

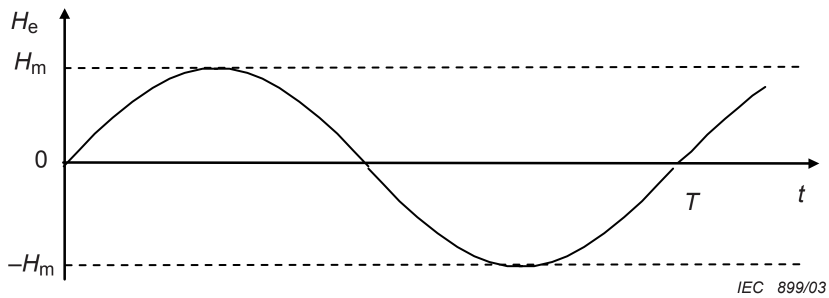

Figure E.1a – Sine waveform with a period *T* = 1/*f*

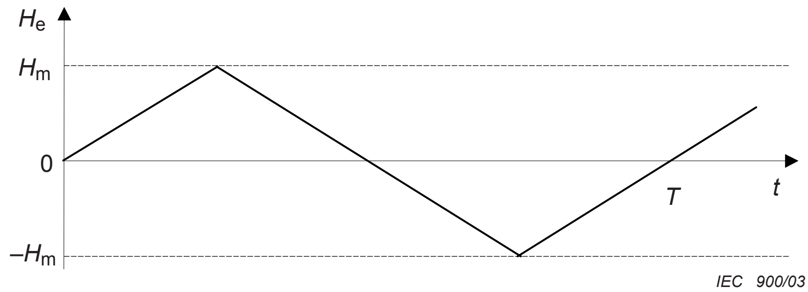

Figure E.1b – Triangular waveform

Figure E.1 – Waveforms of applied magnetic field with a period *T* = 1/*f*

Annex F
(informative)

Uncertainty considerations

F.1 Overview

In 1995, a number of international standards organizations, including IEC, decided to unify the use of statistical terms in their standards. It was decided to use the word “uncertainty” for all quantitative (associated with a number) statistical expressions and eliminate the quantitative use of “precision” and “accuracy.” The words “accuracy” and “precision” could still be used qualitatively. The terminology and methods of uncertainty evaluation are standardized in the Guide to the Expression of Uncertainty in Measurement (GUM) [1] [2)].

It was left to each TC to decide if they were going to change existing and future standards to be consistent with the new unified approach. Such change is not easy and creates additional confusion especially for those who are not familiar with statistics and the term uncertainty. At the June 2006 TC 90 meeting in Kyoto, it was decided to implement these changes in future standards.

Converting “accuracy” and “precision” numbers to the equivalent “uncertainty” numbers requires knowledge about the origins of the numbers. The coverage factor of the original number may have been 1, 2, 3, or some other number. A manufacturer’s specification that can sometimes be described by a rectangular distribution will lead to a conversion number of $1/\sqrt{3}$. The appropriate coverage factor was used when converting the original number to the equivalent standard uncertainty. The conversion process is not something that the user of the standard needs to address for compliance to TC 90 standards, it is only explained here to inform the user about how the numbers were changed in this process. The process of converting to uncertainty terminology does not alter the user’s need to evaluate their measurement uncertainty to determine if the criteria of the standard are met.

The procedures outlined in TC 90 measurement standards were designed to limit the uncertainty of any quantity that could influence the measurement, based on the Convener’s engineering judgment and propagation of error analysis. Where possible, the standards have simple limits for the influence of some quantities so that the user is not required to evaluate the uncertainty of such quantities. The overall uncertainty of a standard was then confirmed by an interlaboratory comparison.

F.2 Terms and definitions

Statistical terms and definitions can be found in three sources: the GUM, the International Vocabulary of Basic and General Terms in Metrology (VIM)[2], and the NIST Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results (NIST)[3]. Not all statistical terms and definitions used in this standard are explicitly defined in the GUM. For example, the terms “relative standard uncertainty” and “relative combined standard uncertainty” are used in the GUM (5.1.6, Annex J), but they are not formally defined in the GUM (see [3]).

F.3 Consideration of the uncertainty concept

Statistical evaluations in the past frequently used the Coefficient of Variation (*COV*) which is the ratio of the standard deviation and the mean (N.B. the *COV* is often called the relative standard deviation). Such evaluations have been used to assess the precision of the measurements and

2) Figures in square brackets refer to the reference documents in Clause F.5 of this Annex.

give the closeness of repeated tests. The standard uncertainty (SU) depends more on the number of repeated tests and less on the mean than the *COV* and therefore in some cases gives a more realistic picture of the data scatter and test judgment. The example below shows a set of electronic drift and creep voltage measurements from two nominally identical extensometers using same signal conditioner and data acquisition system. The n = 10 data pairs are taken randomly from the spreadsheet of 32 000 cells. Here, extensometer number one (E_1) is at zero offset position whilst extensometer number two (E_2) is deflected to 1 mm. The output signals are in Volts.

Table F.1 – Output signals from two nominally identical extensometers

Output signal [V]	
E_1	E_2
0,001 220 70	2,334 594 73
0,000 610 35	2,334 289 55
0,001 525 88	2,334 289 55
0,001 220 70	2,334 594 73
0,001 525 88	2,334 594 73
0,001 220 70	2,333 984 38
0,001 52 588	2,334 289 55
0,000 915 53	2,334 289 55
0,000 915 53	2,334 594 73
0,001 220 70	2,334 594 73

Table F.2 – Mean values of two output signals

Mean ($\overline{X}$) [V]	
E_1	E_2
0,001 190 19	2,334 411 62

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \quad [\text{V}] \tag{F.1}$$

Table F.3 – Experimental standard deviations of two output signals

Experimental standard deviation (s) [V]	
E_1	E_2
0,000 303 48	0,000 213 381

$$s = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(X_i - \overline{X}\right)^2} \quad [\text{V}] \tag{F.2}$$

Table F.4 – Standard uncertainties of two output signals

Standard uncertainty (u) [V]	
E_1	E_2
0,000 095 97	0,000 067 48

$$u = \frac{s}{\sqrt{n}} \quad [\mathrm{V}] \tag{F.3}$$

Table F.5 – Coefficient of variations of two output signals

Coefficient of Variation (COV) [%]	
E_1	E_2
25,498 2	0,009 1

$$COV = \frac{s}{\overline{X}} \tag{F.4}$$

The standard uncertainty is very similar for the two extensometer deflections. In contrast the coefficient of variation *COV* is nearly a factor of 2 800 different between the two data sets. This shows the advantage of using the standard uncertainty which is independent of the mean value.

F.4 Uncertainty evaluation example for TC 90 standards

The observed value of a measurement does not usually coincide with the true value of the measurand. The observed value may be considered as an estimate of the true value. The uncertainty is part of the "measurement error" which is an intrinsic part of any measurement. The magnitude of the uncertainty is both a measure of the metrological quality of the measurements and improves the knowledge about the measurement procedure. The result of any physical measurement consists of two parts: an estimate of the true value of the measurand and the uncertainty of this "best" estimate. The GUM, within this context, is a guide for a transparent, standardized documentation of the measurement procedure. One can attempt to measure the true value by measuring "the best estimate" and using uncertainty evaluations which can be considered as two types: type A uncertainties (repeated measurements in the laboratory in general expressed in the form of Gaussian distributions) and type B uncertainties (previous experiments, literature data, manufacturer's information, etc. often provided in the form of rectangular distributions).

The calculation of uncertainty using the GUM procedure is illustrated in the following example:

a) The user must derive in a first step a mathematical measurement model in form of identified measurand as a function of all input quantities. A simple example of such a model is given for the uncertainty of a force measurement using a load cell:

   Force as measurand = W (weight of standard as expected) + d_W (manufacturer's data) + d_R (repeated checks of standard weight/day) + d_{Re} (reproducibility of checks at different days).

   Here the input quantities are: the measured weight of standard weights using different balances (type A), manufacturer's data (type B), repeated test results using the digital electronic system (type B), and reproducibility of the final values measured on different days (type B).

b) The user should identify the type of distribution for each input quantity (e.g. Gaussian distributions for type A measurements and rectangular distributions for type B measurements).

c) Evaluate the standard uncertainty of the type A measurements,

$u_A = \frac{s}{\sqrt{n}}$ where, s is the experimental standard deviation and n is the total number of measured data points.

d) Evaluate the standard uncertainties of the type B measurements:

$u_B = \sqrt{\frac{1}{3} \cdot {d_W}^2 + ...}$ where, d_W is the range of rectangular distributed values

e) Calculate the combined standard uncertainty for the measurand by combining all the standard uncertainties using the expression:

$u_c = \sqrt{u_A^2 + u_B^2}$

In this case, it has been assumed that there is no correlation between input quantities. If the model equation has terms with products or quotients, the combined standard uncertainty is evaluated using partial derivatives and the relationship becomes more complex due to the sensitivity coefficients [4, 5].

f) Optional - the combined standard uncertainty of the estimate of the referred measurand can be multiplied by a coverage factor (e. g. 1 for 68 % or 2 for 95 % or 3 for 99 %) to increase the probability that the measurand can be expected to lie within the interval.

g) Report the result as the estimate of the measurand ± the expanded uncertainty, together with the unit of measurement, and, at a minimum, state the coverage factor used to compute the expanded uncertainty and the estimated coverage probability.

To facilitate the computation and standardize the procedure, use of appropriate certified commercial software is a straightforward method that reduces the amount of routine work [6, 7]. In particular, the indicated partial derivatives can be easily obtained when such a software tool is used. Further references for the guidelines of measurement uncertainties are given in [3, 8, and 9].

F.5 Reference documents of this annex F

[1] ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

[2] ISO/IEC Guide 99:2007, *International vocabulary of metrology – Basic and general concepts and associated terms(VIM)*

[3] TAYLOR, B.N. and KUYATT, C.E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.* NIST Technical Note 1297 (1994) (Available at <http://physics.nist.gov/Pubs/pdf.html>)

[4] KRAGTEN, J., Calculating standard deviations and confidence intervals with a universally applicable spreadsheet technique. *Analyst*, **119**, 2161-2166 (1994)

[5] EURACHEM / CITAC Guide CG 4 Second edition:2000, *Quantifying Uncertainty in Analytical Measurement*

[6] Available at <http://www.gum.dk/e-wb-home/gw_home.html>

[7] Available at <http://www.isgmax.com/>

[8] CHURCHILL, E., HARRY, H.K., and COLLE, R., *Expression of the Uncertainties of Final Measurement Results.* NBS Special Publication 644 (1983)

[9] JAB NOTE4 Edition 1:2003, *Estimation of Measurement Uncertainty (Electrical Testing / High Power Testing).* (Available at <http://www.jab.or.jp>).

Annex G
(informative)

Evaluation of uncertainty in AC loss measurement by pickup coil method [13]

Uncertainty in AC loss measurement by the pickup coil method is mainly attributed to effects of measurement conditions, signal processing and division of the AC loss into the components. The effect of the measurement conditions is evaluated with theoretical expressions of two main components in the AC loss, the hysteresis loss P_h and the coupling loss P_c. The signal processing is an essential step to calculate the AC loss with experimental outputs by Equations (1) and (2). The third is an additional one to divide the AC loss into the two components by following the procedures in 8.5 and 8.6. Main results of the relative combined standard uncertainties for the two loss components in these evaluations are summarized in Table G1 as a typical example for NbTi conductors.

The uncertainty evaluation for the effect of the measurement conditions starts from basic standard uncertainties for temperature and magnetic field, where the specimen is set, in addition to those of measurement apparatuses. These initial data are given in the text and Table G1. The propagation of the initial standard uncertainties to those of P_h and P_c can be estimated by the following theoretical expressions

$$P_h = \frac{4}{3}\mu_0 H_p{}^2\left(2\frac{H_m}{H_p} - 1\right)f \cong \frac{8}{3}\mu_0 H_p H_m f \quad \text{(G.1)}$$

$$P_c = 4\pi^2 \tau \mu_0 H_m{}^2 f^2 \quad \text{(G.2)}$$

through the penetration field H_p and the coupling time constant τ. We shall consider that the AC loss is almost corresponding to the hysteresis loss at a lower frequency limit in the measurement and equivalently divided into the two components at an upper one. The relative combined standard uncertainties of the AC loss are expressed as

$$u_{c,r1}(P_{lower}) = u_{c,r1}(P_h) \quad \text{at the lower frequency limit} \quad \text{(G.3)}$$

$$u_{c,r1}(P_{upper}) = \sqrt{\alpha^2 u_{c,r1}{}^2(P_h) + (1-\alpha)^2 u_{c,r1}{}^2(P_c)} \quad \text{at the upper frequency limit} \quad \text{(G.4)}$$

where $u_{c,r1}(P_h)$ and $u_{c,r1}(P_c)$ are the relative combined standard uncertainties of P_h and P_c, respectively, obtained from Equations (G.1) and (G.2). The coefficient α is the ratio of the hysteresis loss to the total AC loss at the upper frequency limit, where it is assumed that $u_{c,r1}(P_h)$ and $u_{c,r1}(P_c)$ are independent. It is recommended that the α value be set in a range from 0,3 to 0,5. Table G1 gives the results of the uncertainty evaluation for α = 0,5 as a typical example.

In the signal processing, Equations (1) and (2) are used to evaluate the uncertainty. The basic standard uncertainties for this step are also listed in Table G1. Only the relative combined standard uncertainty of the total AC loss, $u_{c,r2}(P)$ is evaluated in this stage. The uncertainty of $U_{p\text{-}c}$ in (2) almost equivalent to that of the original signal from the pickup coil is assumed in the evaluation under the condition of a full compensation. The results in these two steps shall be integrated for the relative combined standard uncertainty $u_{c,r}(P)$ of the AC loss as

$$u_{c,r}(P) = u_{c,r}(P_{lower}) = \sqrt{u_{c,r1}{}^2(P_{lower}) + u_{c,r2}{}^2(P)} \quad \text{at the lower frequency limit} \quad \text{(G.5)}$$

$$= u_{c,r}(P_{upper}) = \sqrt{u_{c,r1}{}^2(P_{upper}) + u_{c,r2}{}^2(P)} \quad \text{at the upper frequency limit.} \quad \text{(G.6)}$$

Finally, the relative combined standard uncertainties of the components P_h and P_c are evaluated from that of the total AC loss at the lower and upper frequency limits. The relative combined standard uncertainty $u_{c,r}(P_h)$ of P_h is considered to be that of the AC loss at the lower frequency limit. In this way, the relative combined standard uncertainty $u_{c,r}(P_c)$ of P_c is estimated from the AC loss at the upper frequency limit in the following,

$$u_{u,r}(P_h) = u_{u,r}(P_{lower}) \tag{G.7}$$

$$u_{c,r}(P_c) = \sqrt{\left(\frac{\alpha}{1-\alpha}\right)^2 u_{c,r}{}^2(P_h) + \left(\frac{1}{1-\alpha}\right)^2 u_{c,r}{}^2(P_{upper})} = \sqrt{\left(\frac{\alpha}{1-\alpha}\right)^2 u_{c,r}{}^2(P_{lower}) + \left(\frac{1}{1-\alpha}\right)^2 u_{c,r}{}^2(P_{upper})} \tag{G.8}$$

where the condition that the averages of P_h and P_c are equivalent to each other at the upper limit is used. The relative combined standard uncertainty of the coupling time constant is also evaluated with Equation (G.2).

In the whole processes of the evaluation, the uncertainties are affected mainly by the temperature for the hysteresis loss, and the temperature and the final step of loss division for the coupling loss and the coupling time constant.

The target relative combined standard uncertainty of this method is defined as an expanded uncertainty U_r with a coverage factor k of 2 as

$$U_r = 2\ u_{c,r} \tag{G.9}$$

for the relative combined standard uncertainty $u_{c,r}$ of the hysteresis loss and the coupling loss (the coupling time constant).

In the past round robin tests [7], [8], *COV* was used to summarize the international comparison. The relationship between *COV* and the uncertainty of each AC loss component calculated in accordance with the procedure in Annex G is discussed in the bibliography [10].

Table G.1 – Propagation of relative uncertainty in the pickup coil method (α = 0,5)

Effect of measurement conditions		Effect of signal processing in measuremnt	
Measurement apparatus	$5,0 \times 10^{-3}$	Turn number of pickup coil	$1,5 \times 10^{-3}$
Magnetic field	$5,0 \times 10^{-3}$	Cross sectional area of pickup coil	$1,0 \times 10^{-2}$
Temperature	$1,2 \times 10^{-2}$	Sampling interval of measurement	$1,4 \times 10^{-6}$
Penetration magnetic field H_p	$3,6 \times 10^{-2}$	Terminal voltage of pickup coil	$3,2 \times 10^{-6}$
Coupling time constant τ	$1,4 \times 10^{-2}$	Processing magnetic field	$1,0 \times 10^{-2}$
Hysteresis loss	$3,7 \times 10^{-2}$	Processing total AC loss	$1,0 \times 10^{-2}$
Coupling loss	$2,0 \times 10^{-2}$	Integrating two effects	
AC loss in lower frequency limit	$3,7 \times 10^{-2}$	AC loss in lower frequency limit	$3,8 \times 10^{-2}$
AC loss in upper frequency limit	$2,1 \times 10^{-2}$	AC loss in upper frequency limit	$2,3 \times 10^{-2}$
Division of AC loss into components			
Hysteresis loss			$3,8 \times 10^{-2}$
Coupling loss			$5,4 \times 10^{-2}$
Coupling time constant			$5,5 \times 10^{-2}$
Relative expanded uncertainty with k = 2			
Hysteresis loss			$7,6 \times 10^{-2}$
Coupling loss			$10,8 \times 10^{-2}$
Coupling time constant			$11,0 \times 10^{-2}$

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