IEC 60404-6

Edition 3.0 2018-05
REDLINE VERSION

INTERNATIONAL STANDARD

colour inside

Magnetic materials –
Part 6: Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to ~~200~~ 100 kHz by the use of ring specimens

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International Standard IEC 60404-6 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

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

This edition includes the following significant technical changes with respect to the previous edition:

a) adaption to modern measurement and evaluation methods, in particular the introduction of the widely spread digital sampling method for the acquisition and evaluation of the measured data;
b) limitation of the frequency range up to 100 kHz;
c) deletion of Clause 7 of the second edition that specified the measurement of magnetic properties using a digital impedance bridge;
d) addition of a new Clause 7 on the measurement of the specific total loss by the wattmeter method, including an example of the application of the digital sampling method;
e) addition of an informative annex on the technical details of the digital sampling technique for the determination of magnetic properties.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
68/595/FDIS	68/600/RVD

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

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

A list of all parts in the IEC 60404 series, published under the general title *Magnetic materials*, can be found on the IEC website.

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

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- withdrawn,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

The contents of the corrigendum of November 2018 have been included in this copy.

IMPORTANT – The "colour inside" logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this publication using a colour printer.

INTRODUCTION

This edition of IEC 60404-6 has been prepared by WG2 in the TC68 maintenance programme of publications. The d.c. measurements in the first edition of this standard are now covered in IEC 60404-4 and Amendment 1 to that standard. This edition of IEC 60404-6 includes measurements on magnetically soft powder materials. Since measurements on these materials at high frequencies employ some of the techniques used to measure magnetic components, there has been active collaboration with IEC TC51. IEC TC51 recently started to publish the new IEC 62044 series which will be composed of four parts. IEC 62044-3 presents methods of measurement of magnetic properties at high excitation levels appropriate to various ferrite core applications, whereas this edition of IEC 60404-6 covers the requirements of material measurements excluding ferrites, so that the two standards do not overlap.

MAGNETIC MATERIALS –

Part 6: Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to ~~200~~ 100 kHz by the use of ring specimens

1 Scope

This part of IEC 60404 specifies methods for the measurement of AC magnetic properties of soft magnetic materials, other than electrical steels and soft ferrites, in the frequency range 20 Hz to ~~200~~ 100 kHz. The materials covered by this part of IEC 60404 include those speciality alloys listed in IEC 60404-8-6, amorphous and nano-crystalline soft magnetic materials, pressed and sintered and metal injection moulded parts such as are listed in IEC 60404-8-9, cast parts and magnetically soft composite materials.

The object of this part is to define the general principles and the technical details of the measurement of the magnetic properties of magnetically soft materials by means of ring methods. For materials supplied in powder form, a ring test specimen is formed by the appropriate pressing method for that material.

~~DC magnetic measurements on magnetically soft materials shall be~~ The measurement of the DC magnetic properties of soft magnetic materials is made in accordance with the ring method of IEC 60404-4. The determinations of the magnetic characteristics of magnetically soft components ~~shall be~~ are made in accordance with IEC 62044-3.

NOTE IEC 62044-3:2000 specifies methods for the measurement of AC magnetic characteristics of magnetically soft components in the frequency range up to 10 MHz.

Normally, the measurements ~~shall be~~ are made at an ambient temperature of (23 ± 5) °C on ~~ring~~ test specimens which have first been magnetized, then demagnetized. Measurements can be made over other temperature ranges by agreement between ~~supplier and purchaser~~ parties concerned.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism*

IEC 60050-221, *International Electrotechnical Vocabulary – Chapter 221: Magnetic materials and components*

IEC 60404-2~~:1996~~, *Magnetic materials – Part 2: Methods of measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame*

IEC 60404-4~~:1995~~, *Magnetic materials – Part 4: Methods of measurement of d.c. magnetic properties of iron and steel*
~~Amendment 1:2000~~

IEC 60404-8-6~~:1999~~, *Magnetic materials – Part 8-6: Specifications for individual materials – Soft magnetic metallic materials*

IEC 60404-8-9:1994, *Magnetic materials – Part 8: Specifications for individual materials – Section 9: Standard specification for sintered soft magnetic materials*

IEC 62044-3:2000, *Cores made of soft magnetic materials – Measuring methods – Part 3: Magnetic properties at high excitation levels*

ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement*, 1993 *(GUM:1995)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-121 and IEC 60050-221 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 General principles of measurement

4.1 Principle of the ring method

The measurements are made on a closed magnetic circuit in the form of a ring test specimen wound with one or two windings.

4.2 Test specimen

The test specimen shall be in the form of a ring of rectangular cross-section which may be formed by

a) winding thin strip or wire to produce a clock-spring wound toroidal core; or

b) punching, laser cutting or photochemically etching a stack of punched, laser cut, wire cut or photochemically etched ring laminations; or

c) pressing and sintering of powders, metal injection moulding, 3D printing or casting.

In the case of powder materials, the production of a ring test specimen by metal injection moulding or by pressing (with heating if applicable) shall be carried out in accordance with the material manufacturer's recommendations to achieve the optimum magnetic performance of the powder material.

For all types of test specimen, burrs and sharp edges should be removed prior to heat treatment. In the case of high permeability material, It is preferable to enclose the ring test specimen in a two-part non-magnetic annular case. The case dimensions shall be such that it closely fits without introducing stress into the material of the test specimen.

The ring shall have dimensions such that the ratio of the outer to inner diameter shall be no greater than 1,4 and preferably less than 1,25 to achieve a sufficiently homogenous magnetization of the test specimen.

For solid and pressed powder materials, the dimensions of the test specimen, that is the outer and inner diameters and the height of the ring, shall be measured with suitable calibrated measuring instruments. The respective dimensions shall be measured at several locations on a test specimen and averaged. The cross-sectional area of the test specimen shall be calculated from Formula (1).

$$A = \frac{(D-d)}{2}h \tag{1}$$

where

A is the cross-sectional area of the test specimen, in square metres;

D is the outer diameter of the test specimen, in metres;

d is the inner diameter of the test specimen, in metres;

h is the height of the test specimen, in metres.

For a stack of laminations or a toroidal wound core, the cross-sectional area of the test specimen shall be calculated from the mass, density and the values of the inner and outer diameter of the ring specimen. The mass and diameters shall be measured with suitable calibrated instruments. The density shall be the conventional density for the material supplied by the manufacturer. The cross-sectional area shall be calculated from Formula (2).

$$A = \frac{2m}{\rho\pi(D+d)} \tag{2}$$

where

m is the mass of the test specimen, in kilograms;

ρ is the density of the material, in kilograms per cubic metre.

For the calculation of the magnetic field strength ~~use~~ the mean magnetic path length of the test specimen determined from Formula (3) shall be used.

$$l_m = \pi\frac{(D+d)}{2} \tag{3}$$

where

l_m is the mean magnetic path length of the test specimen, in metres.

NOTE For measurements of magnetically soft components, an effective core cross-sectional area and an effective magnetic path length are used (described in IEC 62044-3:2000). The difference in results between material measurements and component measurements is larger when the ratio of the outer to inner diameter is larger.

If the specific total loss is to be determined, ~~then~~ the mass of the test specimen shall be measured with a suitable calibrated balance.

4.3 Windings

The test specimen shall be wound with a magnetizing winding and a secondary winding (see Annex A).

The numbers of ~~windings and~~ turns depend upon the measuring equipment and method being used. ~~For specific total loss measurements, a magnetizing and a secondary winding are normally required. In this case,~~ The secondary winding shall be wound as closely as possible to the test specimen to minimize the effect of air flux ~~included in~~ enclosed between the test specimen and the secondary winding. All windings shall be wound uniformly over the whole length of the test specimen.

For measurements at frequencies above power frequencies, care shall be taken to avoid complications related to capacitance and other effects. These are introduced and discussed in Annex A.

Care shall be taken to ensure that the wire insulation is not damaged during the winding process causing a short circuit to the test specimen. An electrical check shall be made with a suitable AC insulation resistance measuring device to ensure that there is no direct connection between the windings and the test specimen.

5 Temperature measurements

When the temperature of the surface of the test specimen is required, it shall be measured by affixing a calibrated non-magnetic thermocouple (for example a type T thermocouple) to the test specimen. Where the test specimen is ~~encapsulated~~ enclosed in an annular case, a small hole shall be made in the ~~encapsulation~~ case, taking care not to damage the material of the test specimen, and the thermocouple fixed in contact with the ~~core material~~ test specimen. If this is not possible, the thermocouple shall be affixed to the ~~encapsulation~~ case and this procedure shall be reported in the test report. The thermocouple shall be connected to a suitable calibrated ~~digital~~ voltmeter in order to measure its output voltage which can be related to the corresponding temperature through the calibration tables for the thermocouple.

Where the temperature of the test specimen is found to vary with time after magnetization, the measurements of the magnetic properties shall be carried out either when an agreed temperature is reached or after a time agreed between the ~~purchaser and supplier~~ parties concerned. If measurements are to be made at elevated temperatures, these may be carried out with the test specimen placed in a suitable oven to produce the required temperature.

~~NOTE~~ A second smaller time-dependent magnetic relaxation effect ~~may~~ can also affect the magnetic properties. For the types of materials covered by this document, the effect is usually masked by temperature changes. However, if such magnetic relaxation effects become apparent, then the test specimen should ~~be allowed to~~ dwell at the prescribed magnetic flux density or magnetic field strength for an agreed period of time before making the final measurements.

6 Measurement of ~~magnetic~~ the relative amplitude permeability and the AC magnetization curve ~~using the voltmeter-ammeter method~~

6.1 ~~Introduction~~ General

The measurements are made using the ring method at frequencies normally from 20 Hz to ~~200~~ 100 kHz, the upper frequency being limited by the performance of the instrumentation.

~~NOTE~~ Where suitable calibrated instruments exist and careful winding to reduce interwinding capacitance has been performed, this upper limit may be extended to 1 MHz (See Annex A).

~~NOTE DC measurements should be made in accordance with the ring method described in IEC 60404-4.~~

~~NOTE A selection of methods for the measurement of loss and effective permeability of cores, taken from current production, at high excitation levels and at frequencies ranging from practically d.c. to 10 MHz and even higher, is given in 6.2 and 6.3 of IEC 62044-3.~~

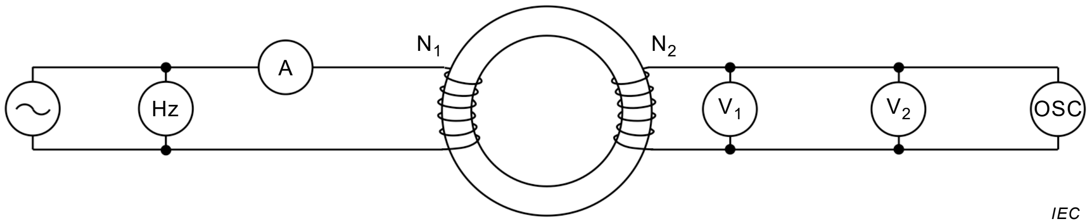
6.2 Apparatus and connections

~~The ring test specimen shall be wound with a magnetizing winding, N_1, and a secondary winding, N_2 (see 3.2 and Annex A).~~

The apparatus shall be connected as shown in Figure 1.

NOTE 1 Figure 3 can be used for the measurement of the relative amplitude permeability and the magnetization curve using the digital sampling technique.

NOTE 2 For the application of digital sampling technique, see Annex B.



Key

~	power supply (usually an oscillator and a power amplifier)
A	true r.m.s. or peak reading ammeter, or a true r.m.s. or peak reading voltmeter and a non-inductive precision resistor to measure the magnetizing current
Hz	frequency meter
N_1	magnetizing winding
N_2	secondary winding
OSC	oscilloscope
V_1	average type voltmeter
V_2	r.m.s. voltmeter

Figure 1 – Circuit of the ~~ring method~~ measurement apparatus

~~NOTE~~ When conducting sinusoidal current measurements, a non-inductive precision resistor should be connected in series with the magnetizing winding N_1 to guarantee that the magnetizing circuit resistance is at least ten times greater than the impedance of the magnetizing winding N_1 on the test specimen.

The source of alternating current shall have a variation of voltage and frequency at its output individually not exceeding ± 0,2 % of the adjusted value during the measurement. It shall be connected to a true r.m.s. or peak reading ammeter, or a true r.m.s. or peak reading voltmeter and a parallel non-inductive precision resistor, in series with the magnetizing winding N_1 on the ~~ring~~ test specimen, to measure the magnetizing current.

The secondary circuit comprises a secondary winding N_2 connected to two voltmeters in parallel. One voltmeter V_2 measures the true r.m.s. value, the other voltmeter V_1 measures the average rectified value but is sometimes scaled in values 1,111 times the rectified value.

~~NOTE~~ The waveform of the induced secondary voltage that is induced in the secondary winding N_2 should be checked with an oscilloscope to ensure that only the fundamental component is present.

6.3 Waveform of induced secondary voltage or magnetizing current

In order to obtain comparable measurements, it shall be agreed prior to the measurements that either the waveform of the induced secondary voltage or the waveform of the magnetizing current shall be maintained sinusoidal with a form factor of 1,111 with a relative tolerance of ± 1 %. In the latter case, a non-inductive precision resistor connected in series with the magnetizing ~~circuit~~ winding is required.

NOTE 1 The waveform of the induced secondary voltage and the magnetizing current can be measured by the digital sampling technique. See Figure 3 and Annex B.

~~NOTE~~ The time constant of the non-inductive precision resistor should be checked to be low to ensure that the waveform is within the specified limits.

~~NOTE~~ The non-inductive precision resistor ~~can~~ may be the same resistor as used for the measurement of the magnetizing current.

NOTE 2 Sinusoidal waveform control ~~may~~ can be achieved by digital means (see Annex C).

At frequencies in the range 20 Hz to 50 kHz, the form factor of the induced secondary voltage can be determined by connecting two voltmeters having a high impedance (typically > 1 MΩ in parallel with 90 pF to 150 pF) across the secondary winding. One voltmeter shall be responsive to the r.m.s. value of voltage and ~~one~~ the other shall be responsive to the average rectified value of the ~~secondary~~ voltage. The form factor is then determined from the ratio of the r.m.s. value to the average rectified value.

~~NOTE~~ For optimum power transfer, it may be necessary to optimize the number of turns of the magnetizing winding to match the output impedance of the power ~~source~~ supply. This can be determined from Formula (4).

$$Z = \mathrm{j}\omega L \tag{4}$$

where

- Z is the output impedance of the power ~~source~~ supply, in ohms;
- j is the complex number sign;
- ω is the angular frequency of the output of the power ~~source~~ supply, in radians per second;
- L is the effective inductance of the magnetizing winding of the ~~ring~~ test specimen, in henrys, calculated from Formula (5).

$$L = \frac{N_1^2 A \mu_0 \mu_r}{l_m} \tag{5}$$

where

- N_1 is the number of turns of the magnetizing winding;
- A is the cross-sectional area of the test specimen, in square metres;
- μ_0 is the magnetic constant ($4\,\pi \times 10^{-7}$ henrys per metre);
- μ_r is the relative amplitude permeability of the test specimen;
- l_m is the mean magnetic path length of the test specimen, in metres.

Where the relative ~~magnetic~~ amplitude permeability is not known, a preliminary measurement may need to be made of the peak values of magnetic field strength and magnetic flux density as described in 6.4.1 and 6.4.2 and the relative ~~magnetic~~ amplitude permeability calculated as described in 6.4.3.

6.4 Determination of characteristics

6.4.1 Determination of the peak value of the magnetic field strength

The peak value of magnetic field strength at which the measurement is to be made is calculated from Formula (6).

$$\sout{H = \frac{N_1 I}{\ell_m}} \qquad \hat{H} = \frac{N_1 \hat{I}}{l_m} \tag{6}$$

where

- ~~H~~ $\hat{H}$ is the peak value of the magnetic field strength, in amperes per metre;
- N_1 is the number of turns of the magnetizing winding on the test specimen;
- ~~I~~ $\hat{I}$ is the peak value of the magnetizing current, in amperes;
- l_m is the mean magnetic path length of the test specimen, in metres.

Normally the amplitude of the magnetic field strength is determined by measuring the r.m.s. magnetizing current and multiplying by the square root of 2. For sinusoidal magnetizing current, this defines the correct value of the peak value of magnetic field strength. For sinusoidal magnetic flux density, this defines an equivalent peak value of magnetic field strength, which is numerically lower for a given magnetizing current. As an alternative, the peak value of magnetic field strength can be determined using a calibrated peak reading ammeter or a peak reading voltmeter and a non-inductive precision resistor.

Prior to measurement, the test specimen shall be carefully demagnetized from a value of field strength of not less than ten times the coercivity by slowly reducing the corresponding magnitude of the magnetizing current to zero. Demagnetization shall be carried out at the same or lower frequency as will be used for the measurements.

6.4.2 Determination of the peak value of the magnetic flux density

The average rectified value of the induced secondary voltage shall be measured using ~~the~~ a calibrated average type voltmeter ~~V_1~~ or a digitizer (see Figure 3), and the peak value of the magnetic flux density shall be calculated from Formula (7).

~~$\overline{|U_2|} = 4\,f\,A\,\hat{B}\,N_2$~~

$$\hat{B} = \frac{1}{4\,f N_2 A}\overline{|U_2|} \tag{7}$$

where

$\hat{B}$ is the peak value of magnetic flux density, in teslas;

$\overline{|U_2|}$ is the average rectified value of the induced secondary voltage, in volts;

f is the frequency, in hertz;

A is the cross-sectional area of the test specimen, in square metres.

N_2 is the number of turns of the secondary winding.

NOTE For the application of the digital sampling technique, see Annex B.

Depending on the level of magnetic field strength and the ratio of the cross-sectional areas of the test specimen and the secondary winding, it may be necessary to make a correction to the magnetic flux density for the air flux enclosed between the test specimen and the secondary winding. The corrected value B of the magnetic flux density is given by Formula (8).

$$B = B' - \mu_0 H \frac{(A' - A)}{A} \tag{8}$$

where

B' is the measured value of magnetic flux density, in teslas;

μ_0 is the magnetic constant ($4\,\pi \times 10^{-7}$ henrys per metre);

H is the magnetic field strength, in amperes per metre;

A' is the cross-sectional area enclosed by the secondary winding, in square metres;

A is the cross-sectional area of the test specimen, in square metres.

6.4.3 Determination of the r.m.s. amplitude permeability and the relative amplitude permeability

For corresponding peak values of magnetic field strength and magnetic flux density, the r.m.s. amplitude permeability shall be calculated from Formula (9).

$$\mu_{a,rms} = \frac{\hat{B}}{\mu_0 \sqrt{2}\, \tilde{H}} \qquad (9)$$

where

$\mu_{a,rms}$ is the r.m.s. amplitude permeability ~~(for sinusoidal magnetic flux density)~~;

~~μ_a is the relative amplitude permeability (for sinusoidal magnetic field strength);~~

μ_0 is the magnetic constant ($4\ \pi \times 10^{-7}$ henrys per metre);

$\hat{B}$ is the peak value of magnetic flux density, in teslas;

$\tilde{H}$ is the r.m.s. value of magnetic field strength, in amperes per metre.

NOTE The relative amplitude permeability, μ_r, can be conventionally expressed as:

$$~~\mu_a = \frac{\hat{B}}{\mu_0 \hat{H}}~~ \qquad \mu_r = \frac{\hat{B}}{\mu_0 \hat{H}} \qquad (10)$$

where

~~μ_a~~ μ_r is the relative amplitude permeability ~~(for sinusoidal magnetic field strength)~~;

μ_0 is the magnetic constant ($4\ \pi \times 10^{-7}$ henrys per metre);

$\hat{B}$ is the peak value of magnetic flux density, in teslas;

$\hat{H}$ is the peak value of magnetic field strength, in amperes per metre.

6.4.4 Determination of the AC magnetization curve

The test specimen shall be carefully demagnetized as described in 6.4.1. By successively increasing the magnetizing current, corresponding peak values of magnetic field strength and magnetic flux density can be obtained from which an AC magnetization curve can be plotted.

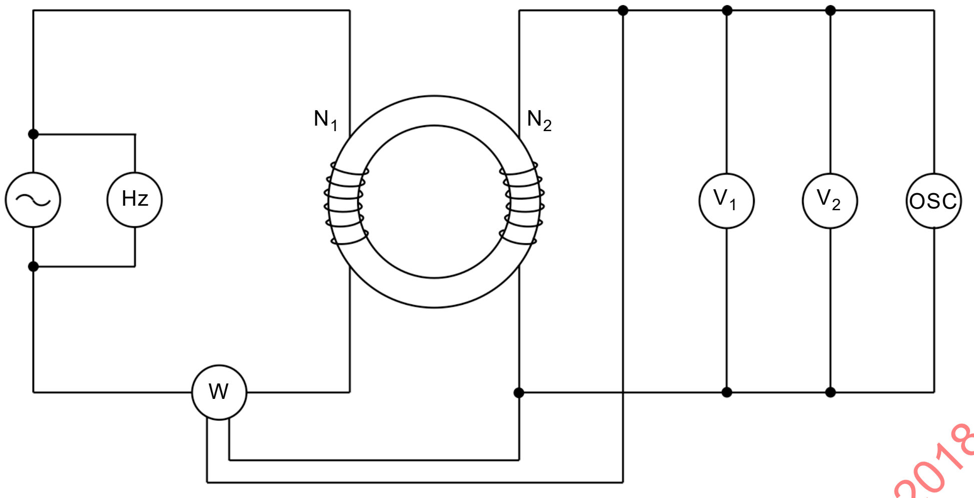
7 Measurement of the specific total loss by the wattmeter method

7.1 Principle of measurement

The principle of measurement is similar to that described in IEC 60404-2 except that the Epstein frame is replaced by the ring test specimen and the instrumentation is capable of making measurements at the required frequency. The measurement of specific total loss shall be done under conditions of sinusoidal magnetic flux density. For some test specimens, this may require the control of the ~~magnetizing current~~ induced secondary voltage waveform (see Annex C) by means of analogue or digital techniques to ensure that sinusoidal magnetic flux density is maintained.

~~NOTE A selection of methods for the measurement of specific total loss and amplitude permeability at high excitation levels at frequencies ranging from practically d.c. to 10 MHz and even higher is given in 6.2 and 6.3 of IEC 62044-3.~~

The apparatus and the windings of the test specimen shall be connected as shown in Figure 2.



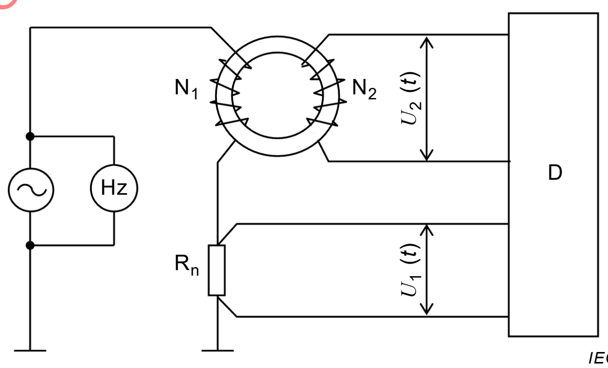
Key

~	power supply (usually an oscillator and amplifier)
Hz	frequency meter
N_1	magnetizing winding
N_2	secondary winding
OSC	oscilloscope
W	wattmeter
V_1	average type voltmeter
V_2	r.m.s. voltmeter

Figure 2 – Circuit of the conventional analogue wattmeter method (also representing the metrological principle of the digital wattmeter method)

For the digital sampling technique, Figure 3 shows a possible circuit structure as an example. In the latter case, a digitizer and supporting software adopt the functions of the oscilloscope, the wattmeter and the voltmeters shown in Figure 2.

NOTE Figure 3 is not the only possible structure of digital sampling technique application, see Annex B.



Key

R_n	non-inductive precision resistor in series with the magnetizing winding to determine the magnetizing current
D	digitizer (usually a digital power analyser or a digital acquisition system with a computer)

Figure 3 – The wattmeter method when connected with the digital sampling technique (example of circuit)

7.2 Voltage measurement

7.2.1 Average type voltmeter~~, V_1~~

The average rectified value of the induced secondary voltage shall be measured using a calibrated average type voltmeter or a calibrated digitizer (see Figures 2 and 3). The load on the secondary circuit shall be as ~~small~~ low as possible (see Annex A). Consequently ~~an electronic~~ a digital voltmeter or digitizer with ~~a~~ high input impedance is required.

NOTE 1 ~~Instruments of this~~ Average type voltmeters are usually graduated in average rectified value multiplied by 1,111.

NOTE 2 For the application of digital sampling technique, see Annex B.

7.2.2 R.M.S. type voltmeter~~, V_2~~

~~A calibrated voltmeter responsive to r.m.s. values shall be used. Again, the load on the secondary circuit shall be as small as possible, an electronic voltmeter being preferred (see Annex A).~~

The true r.m.s. value of the induced secondary voltage shall be measured using a calibrated voltmeter responsive to r.m.s. values or a calibrated digitizer (see Figures 2 and 3). The load on the secondary circuit shall be as low as possible (see Annex A). Consequently a digital voltmeter or digitizer with high input impedance is required.

NOTE For the application of digital sampling technique, see Annex B.

7.3 Power measurement

The power shall be measured using a calibrated wattmeter suitable for circuits which may have a low power factor ($\cos\phi$ down to 0,1) or a calibrated digitizer (see Figures 2 and 3). The input impedance of the voltage circuit shall be as high as possible (see Annex A).

NOTE For the application of digital sampling technique, see Annex B.

7.4 Procedure for the measurement of the specific total loss

The test specimen shall be carefully demagnetized as described in 6.4.1. The current in the magnetizing winding ~~N_1~~ shall be increased until ~~the voltage on voltmeter V_1 (indicating~~ the average rectified voltage~~)~~ corresponds to the required peak value of magnetic flux density calculated from Formula (7).

~~The readings of the two voltmeters V_1 and V_2~~ The average rectified value and the r.m.s. value of the induced secondary voltage shall be recorded and the form factor of the secondary waveform shall be calculated and verified in accordance with 6.2. The wattmeter reading shall then be recorded.

NOTE For the application of digitizing methods, see Annex B.

7.5 Determination of the specific total loss

The power P_m measured by the wattmeter includes the power consumed by the instruments in the secondary circuit, which to a first approximation is equal to ~~$(1{,}111 |U_2|)^2 / R_i$~~ $\tilde{U}_2^2 / R_i$,since the induced secondary voltage is essentially sinusoidal.

Thus, the total loss P_c of the test specimen shall be calculated in accordance with Formula (11).

$$P_c = \frac{N_1}{N_2} P_m - \frac{(1{,}111 \overline{|U_2|})^2}{R_i} \qquad P_c = \frac{N_1}{N_2} P_m - \frac{\tilde{U}_2^{\,2}}{R_i} \qquad (11)$$

where

P_c is the calculated total loss of the test specimen, in watts;

P_m is the power measured by the wattmeter, in watts;

N_1 is the number of turns of the magnetizing winding;

N_2 is the number of turns of the secondary winding;

$\overline{|U_2|}$ is the average rectified value of the secondary voltage, in volts;

$\tilde{U}_2$ is the r.m.s. value of the induced secondary voltage, in volts;

R_i is the combined equivalent resistance of the instruments connected to the secondary winding, in ohms.

The specific total loss P_s shall be obtained by dividing P_c by the mass of the test specimen. Hence,

$$P_s = \frac{P_c}{m} \qquad (12)$$

where

P_s is the specific total loss of the test specimen, in watts per kilogram;

m is the mass of the test specimen, in kilograms.

7 Measurement of magnetic properties using a digital impedance bridge

7.1 Principle of measurement

Digital impedance bridges (also known as impedance analyzers and LCR meters) are widely used to measure the inductance and other technological properties of magnetic components. These instruments can be used to determine magnetic properties such as the a.c. inductance permeability and specific total loss, provided certain restrictions are observed. This method assumes that the ring test specimen is electrically equivalent to a parallel combination of an inductance and a resistance. The a.c. inductance permeability is computed from the inductance while the specific total loss is computed from the resistance.

NOTE 1 LCR meters are generally used for comparative measurements only.

NOTE 2 AC inductance permeability is the permeability determined from the measured inductive component of the impedance of the electrical circuit whereby the magnetic test specimen – under conditions where the magnetic flux density is varying sinusoidally with time with an average value of zero – is represented by the inductive component in parallel with a resistive component.

Testing according to this method shall be restricted to the initial linear region of the magnetization curve where sinusoidal magnetic flux density and magnetic field strength conditions prevail. The test specimen shall be prepared according to 3.1. A single winding (N_1) of sufficient number of turns to maintain sinusoidal magnetic flux density shall be applied.

7.2 Apparatus

The test apparatus is illustrated in Figure 3 and consists of the components shown.

7.2.1 Digital impedance bridge

The calibrated digital impedance bridge shall be of the 4-wire Kelvin type configuration and shall be configured to measure the parallel inductance (L_p) and parallel resistance (R_p). The signal source output impedance shall be sufficiently low as to ensure sinusoidal magnetic flux density is obtained in the test core. The bridge shall have the capability of compensating (nulling) the impedance of the connecting leads between the instrument and test specimen.

7.2.2 True r.m.s. ammeter

A calibrated true r.m.s. ammeter shall be used to measure the magnetizing current. The magnetizing current can also be measured by connecting a non-inductive precision resistor in series with the magnetizing winding and measuring the voltage across it with a calibrated r.m.s. voltmeter. The requirement for a separate meter is waived if the digital impedance meter has an internal ammeter or if the setting accuracy of the signal source has been independently verified.

7.2.3 Average type voltmeter

The average rectified value of the secondary voltage shall be measured using a high input impedance (typically >1 MΩ in parallel with 90 pF to 150 pF) calibrated average type voltmeter.

NOTE Instruments of this type are usually graduated in average rectified value multiplied by 1,111.

7.2.4 RMS voltmeter

A calibrated high input impedance (typically >1 MΩ in parallel with 90 pF to 150 pF) voltmeter responsive to r.m.s. values shall be used.

7.3 Procedure

Prior to measurement, the meter shall be nulled according to the manufacturer's instructions to compensate for the impedance of the test leads. When testing at high frequency, it is desirable to eliminate the impedance due to the winding. This can be done by connecting the meter to a non-magnetic core of the same dimensions as the test specimen and having the same number of winding turns.

After connection of the test specimen to the meter, the specimen shall be demagnetized using either the meter's signal source or an external source. Testing should be conducted either at increasing values of magnetizing current (magnetic field strength) or magnetic flux density. The relationship between magnetic field strength and magnetizing current is given by equation (7),

while the relationship between magnetic flux density and voltage induced in the winding is given by equation (8). The form factor of the voltage induced in the winding shall be determined using the voltages obtained from voltmeters V_1 and V_2. The measured inductances and resistances shall be recorded either manually or by electronic means.

It is not always possible to obtain exactly the required magnetizing current or flux density using digitally controlled instruments. Interpolation of data is necessary in these instances and is permitted by this method.

7.4 Determination of the relative a.c. inductance permeability

The relative a.c. inductance permeability of the test specimen is then calculated from

$$\mu_p = \frac{L_p \ell_m}{N_1^2 A \mu_0} \quad (13)$$

where

μ_p is the relative a.c. inductance permeability;

L_p is the measured parallel inductance, in henrys;

ℓ_m is the mean magnetic path length of the test specimen, in metres;

N_1 is the number of turns of the winding;

A is the cross-sectional area of the test specimen, in square metres;

μ_0 is the magnetic constant ($= 4\ \pi\ 10^{-7}$ henrys per metre).

7.5 Determination of the specific total loss

The specific total loss can be calculated from the measured parallel resistance as follows:

$$P_s = \frac{\left(1{,}111\left|\overline{U_2}\right|\right)^2}{m}\left(\frac{1}{R_p} - \left(\frac{1}{R_p^2} + \frac{1}{\omega^2 L_p^2}\right)R_w\right) \qquad (14)$$

where

P_s is the specific total loss of the test specimen, in watts per kilogram;

$\left|\overline{U_2}\right|$ is the average rectified value of the secondary voltage, in volts;

m is the mass of the test specimen, in kilograms;

R_p is the measured parallel resistance, in ohms;

R_w is the resistance of the primary winding, in ohms (see also Annex A);

L_p is the measured parallel inductance, in henrys;

ω is the angular frequency, in radians per second.

8 Measurement of magnetic properties using digital methods

8.1 Introduction

The measurements are made using the ring method, the upper frequency being limited by the performance of the voltage measuring device and the frequency performance of the non-inductive precision resistor in series with the magnetizing winding to determine the magnetizing current.

8.2 Apparatus and connections

The windings of the ring test specimen shall be connected as shown in Figure 4.

The source of alternating current shall have a variation of voltage and frequency at its output individually not exceeding ±0,2 % of the adjusted value during the measurement. It shall be connected in series with the magnetizing winding N_1 on the ring test specimen and a non-inductive precision resistor across which is a calibrated voltage analogue to digital converter (A/D), V_1.

The secondary circuit comprises a secondary winding N_2 connected to a voltage analogue/digital converter, V_2.

NOTE The resolution of the voltage analogue/digital converter shall be sufficient. The sampling rate of the measuring equipment used should guarantee a sufficient number of samples per period. The sampling of each pair of values must be made simultaneously (for details, see publications on digital signals processing).

8.3 Magnetizing current waveform

In order to obtain comparable measurements, it shall be agreed prior to the measurements that either the waveform of the secondary voltage or the waveform of the magnetizing current shall be maintained sinusoidal with a form factor of 1,111 ± 1 %.

NOTE To produce a good waveform of secondary voltage or magnetizing current it may be necessary to optimise the number of turns of the magnetizing winding to match the output impedance of the power source. This can be determined from conditions given in equations (4) and (5).

8.4 Magnetizing winding

The requirements of 3.2 and Annex A shall be met.

8.5 Determination of the magnetic field strength

The magnetic field strength at which the measurement is to be made is calculated from the following relationship:

$$H(t) = \frac{N_1}{R\ell_m} U_1(t) \tag{15}$$

where

$H(t)$ is the magnetic field strength at a time t, in amperes per metre;

N_1 is the number of turns of the magnetizing winding;

$U_1(t)$ is the voltage at a time t across the non-inductive precision resistor to determine the magnetizing current, in volts;

ℓ_m is the mean magnetic path length, in metres;

R is the resistance of the non-inductive precision resistor in series with the magnetizing winding to determine the magnetizing current, in ohms.

With the discrete values for voltage U_1, the magnetic field strength is calculated as follows:

$$H_i = \frac{N_1}{R\ell_m} U_{1_i} \tag{16}$$

where

H_i is the discrete magnetic field strength, in amperes per metre;

U_{1_i} is the discrete voltage across the non-inductive precision resistor to determine the magnetizing current, in volts.

8.6 Determination of the magnetic flux density

The secondary voltage shall be measured using a calibrated voltage analogue/digital converter and the magnetic flux density shall be calculated from the following equation:

$$B(t) = \frac{1}{N_2 A} \int_0^t U_2(t)\mathrm{d}t + K \tag{17}$$

where

$B(t)$ is the magnetic flux density at a time t, in teslas;

N_2 is the number of turns of the secondary winding;

$U_2(t)$ is the secondary voltage at a time t, in volts;

A is the cross-sectional area of the test specimen, in square metres;

K is such that the time average of $B(t)$ is zero.

8.7 Determination of the relative a.c. permeability

For corresponding values of magnetic field strength and magnetic flux density, the relative a.c. permeability shall be calculated from the following relationship:

$$\mu_a = \frac{\hat{B}}{\mu_0 \hat{H}} \quad (18)$$

where

μ_a is the relative a.c. permeability;

μ_0 is the magnetic constant ($4 \pi \cdot 10^{-7}$ henrys per metre);

$\hat{B}$ is the peak magnetic flux density, in teslas;

$\hat{H}$ is the peak value of the magnetic field strength, in amperes per metre.

8.8 Determination of a.c. magnetization curve

The test specimen shall be carefully demagnetized. By successively increasing the magnetizing current, corresponding values of maximum magnetic field strength and maximum magnetic flux density can be obtained from which an a.c. magnetization curve can be plotted.

8.9 Determination of the specific total loss

The specific total loss P_s corresponds to the area of the hysteresis loop which can be constructed by the respective values for B and H.

Thus, the specific total loss P_s of the specimen shall be calculated in accordance with the following equation:

$$P_s = \frac{fN_1}{N_2 mR} \int_{t=0}^{T} U_1(t) U_2(t) \mathrm{d}t \quad (19)$$

where

P_s is the specific total loss of the test specimen, in watts per kilogram;

f is the frequency, in hertz;

N_1 is the number of turns of the magnetizing winding;

N_2 is the number of turns of the secondary winding;

m is the mass of the test specimen, in kilograms;

R is the resistance of the non-inductive precision resistor in series with the magnetizing winding used to determine the magnetizing current, in ohms;

T is the period where $T = 1/f$, in seconds;

$U_1(t)$ is the voltage at a time t across the non-inductive precision resistor to determine the magnetizing current, in volts;

$U_2(t)$ is the secondary voltage at a time t, in volts.

8 Uncertainties

The individual contributions to the uncertainty of a particular measurement shall be identified and then combined in accordance with the guidelines set out in ISO/IEC Guide 98-3 to the expression of uncertainty in measurement.

9 Test report

The test report shall contain as necessary

a) the type and serial number or mark of the test specimen;

b) the number of turns of the magnetizing ~~windings~~ winding and ~~turns~~ the secondary winding on the test specimen;

c) the mass and dimensions of the test specimen and, for thin material, the density;

d) the frequency;

e) the test method used;

f) the ambient temperature;

g) the surface temperature of the test specimen;

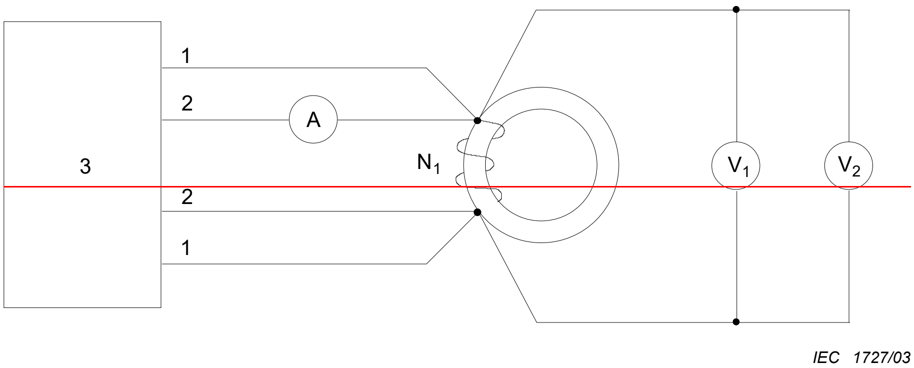
~~h) the time lapse between magnetization and making measurements;~~

h) the method for determining the peak value of the flux density;

i) the nature of the waveform: sinewave of induced secondary voltage or sinewave of magnetizing current;

j) the method for determining the peak ~~current~~ value of magnetizing current;

k) the quantities measured and their uncertainties.



Key

1 potential lead

2 current lead

3 LCR meter

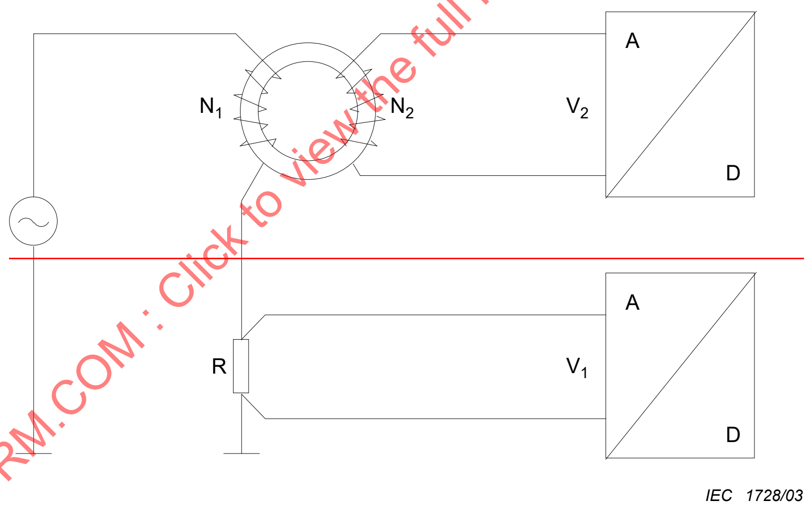
A true r.m.s. ammeter or a true r.m.s. reading voltmeter and precision resistor to measure the magnetizing current

N_1 winding

V_1 average type voltmeter

V_2 r.m.s. voltmeter

Figure 3 – Circuit of the digital impedance bridge method



Key

N_1 magnetizing winding

N_2 secondary winding

R the non-inductive precision resistor in series with the magnetizing winding to determine the magnetizing current

V_1 voltage analogue/digital converter to measure the magnetizing current

V_2 voltage analogue/digital converter to measure the secondary voltage

Figure 4 – Circuit of the digital method

Annex A
(informative)

Guidance on requirements for windings and instrumentation in order to minimise additional losses

A.1 ~~Introduction~~ General

At frequencies above power frequencies, additional losses associated with the windings on the test specimen can occur. These arise from

a) the interwinding capacitance between the magnetizing and secondary windings on the test specimen;

b) the capacitance of the leads from the secondary winding to the ~~measuring~~ instruments;

c) the capacitance and resistance of the input circuits of the ~~measuring~~ instruments; and

d) the dielectric loss of the insulating material of the secondary winding.

A.2 Reduction of additional losses

The magnitude of the additional losses can be minimised by careful choice of winding wire, winding technique and instrumentation.

Wire insulated with a material having a low dielectric loss, for instance polytetrafluorethylene (PTFE) or polyethylene, should be used to minimise the effect of dielectric loss.

Where possible, the magnetizing and secondary windings should be separated to reduce the interwinding capacitance.

The connecting leads from the secondary winding to the ~~measuring~~ instruments should have low dielectric loss insulation and should be kept as short as practicable.

The ~~measuring~~ instruments should have a low input capacitance and high input resistance to avoid loading the secondary ~~winding~~ circuit.

Annex B
(informative)

Digital sampling technique for the determination of magnetic properties and numerical air flux compensation

B.1 General

The digital sampling technique is an advanced technique that is almost exclusively applied to the electrical part of the measurement procedure of this document. Applied to the wattmeter method, it is characterized by the digitization of the induced secondary voltage $U_2(t)$ and the voltage drop $U_1(t)$ across the non-inductive precision resistor in series with the magnetizing winding and by the evaluation of these data for the determination of the magnetic properties of the test specimen (see Figure 3).

For this purpose, instantaneous values of these voltages, having index j, u_{2j} and u_{1j} respectively, are sampled and held simultaneously from the time-dependent voltage signals during a narrow and equidistant time period each by sample-and-hold circuits. They are then immediately converted to digital values by analogue-to-digital converters (ADC). The data pairs sampled over one or more periods together with the test specimen data and the set-up parameters, provide the complete information for one measurement. This data set enables computer processing for the determination of all magnetic properties required in this document.

Whilst the digital sampling technique has perfectly proved its worth applied with the technical frequency range, it is expected that it will be effectively applicable to medium frequencies, i.e. that it can be applied to the measurement procedures which are described in the main part of this document. This expectation is based on the recent availability of fast sample-and-hold electronics. The circuit in Figure 2 applies equally to the analogue methods and the digital sampling technique; the digital sampling technique shown schematically in Figure 3 allows all functions of the measurement equipment shown in Figure 1 and Figure 2 to be realized by a combined system of a data acquisition equipment and software. The control of the sinusoidal waveform of the induced secondary voltage can also be realized by a digital method. However, the purpose and procedure of this technique are different from those of this annex and are treated in Annex C.

Annex B is helpful in understanding the impact of the digital sampling technique on the accuracy achievable by the methods of this document. This is particularly important because ADC circuits, transient recorders and supporting software are readily available and make it possible to establish a sampling wattmeter. The digital sampling technique can offer low uncertainty, but it leads to large errors if improperly used.

NOTE This principle and implementation of digital sampling technique are widely described in many papers and books (IEC 62044-3, [1] and [2][1]).

B.2 Technical details and requirements

The principle of the digital sampling technique is the discretization of voltage and time, i.e. the replacement of the infinitesimal time interval dt by the finite time interval Δt:

1 Numbers in square brackets refer to the Bibliography.

$$\Delta t = \frac{T}{n} = \frac{1}{f \cdot n} = \frac{1}{f_s} \tag{B.1}$$

where:

Δt is the time interval between the sampled points, in seconds;

T is the length of the period of the magnetization, in seconds;

n is the number of instantaneous values sampled over one period;

f is the frequency of the magnetization, in hertz;

f_s is the sampling frequency, in points per second.

In order to achieve lower uncertainties, the length of the period of the magnetization divided by the time interval between the sampled points, i.e. the ratio f_s/f, should be an integer (Nyquist condition [2]) and the sampling frequency, f_s, should be greater than twice the input signal bandwidth.

NOTE If the Nyquist condition is not met, i.e. if the sampling clock and the clock of the signal generator are not synchronized (see paragraph after the next one and paragraph before the last one of B2), the loss of accuracy can be compensated by an increase of the sampling frequency by a factor of at least 5.

The windings of the test specimen are connected with the digital components of the apparatus as shown in Figure 3.

The power supply is usually a computer controlled digital signal generator and a power amplifier. A low pass filter should be inserted between the digital signal generator and the power amplifier to prevent aliasing at the digitizer. The digitizer is usually a calibrated digital power analyzer or a calibrated digital acquisition system with a computer. The digitizer should have a high input impedance (typically >1 MΩ in parallel with 90 pF to 150 pF) to avoid loading the secondary circuit. It is recommended that the sampling clock of the digitizer should be synchronized with the clock of the digital signal generator (Nyquist condition).

The digitizer digitizes the voltage across the non-inductive precision resister and the voltage induced in the secondary winding simultaneously into instantaneous values u_{m1j} and u_{m2j} respectively. The values u_{m1j} and u_{m2j} should be corrected by the factor $\frac{R_i + R}{R_i}$ and $\frac{R_i + R_2}{R_i}$, respectively, to compensate for the voltage drop through the resistances of the instruments in the measuring circuit. Therefore, the values are calculated as follows:

$$u_{1j} = \frac{R_i + R}{R_i} u_{m1j} \tag{B.2}$$

$$u_{2j} = \frac{R_i + R_2}{R_i} u_{m2j} \tag{B.3}$$

where

u_{m1j} is the measured instantaneous value of the voltage across the non-inductive precision resister, in volts;

u_{m2j} is the measured instantaneous value of the voltage induced in the secondary winding, in volts;

u_{1j} is the instantaneous value of the voltage across the non-inductive precision resister, in volts;

u_{2j} is the instantaneous value of the voltage induced in the secondary winding, in volts;

R_i is the input resistance of the digitizer, in ohms;

R is the resistance of the non-inductive precision resistor, in ohms;

R_2 is the resistance of the secondary windings, in ohms.

A computer reconstructs the data arrays of u_{1j} and u_{2j} into numerical signals of voltages $U_1(t)$ and $U_2(t)$, respectively, over one period of magnetization.

Compensation of the effect of air flux on the induced secondary voltage $U_2(t)$ should be achieved by the numerical air flux compensation method (see Clause B.4).

The magnetic flux density $B(t)$ can be calculated by using

$$B(t) = \frac{1}{N_2 A}\left\{\int_0^t U_2(\tau)\mathrm{d}\,\tau - \frac{1}{T}\int_0^T\left(\int_0^t U_2(\tau)\mathrm{d}\,\tau\right)\mathrm{d}\,t\right\} \tag{B.4}$$

The second term in the brackets of Formula (B.4) is the time average over the length of a period which compensates for the integration constant.

The magnetic field strength $H(t)$ can be calculated by using:

$$H(t) = \frac{N_1}{Rl_\mathrm{m}}U_1(t) \tag{B.5}$$

According to an average-sensing voltmeter, the peak value of the flux density can be calculated by the sum of the u_{2j} values sampled over one period as follows:

$$\hat{B} = \frac{1}{4fN_2 A}\frac{1}{T}\int_{t=0}^{T}\left|U_2(t)\right|\mathrm{d}t \cong \frac{1}{4f_\mathrm{s}N_2 A}\sum_{j=0}^{n-1}\left|u_{2j}\right| \tag{B.6}$$

The peak value of the magnetic field strength can be calculated by using:

$$\hat{H} = \frac{N_1}{Rl_\mathrm{m}}\hat{U}_1 \tag{B.7}$$

The calculation of the specific total loss P_s can be carried out by point-by-point multiplication of the u_{1j} and u_{2j} values and summation over one period as follows:

$$P_\mathrm{s} = \frac{1}{l_\mathrm{m}A\rho}\left\{\frac{N_1}{RN_2}\frac{1}{T}\int_{t=0}^{T}U_1(t)U_2(t)\mathrm{d}t - \frac{\widetilde{U}_2^{\,2}}{R_\mathrm{i}+R_2}\right\} \cong \frac{1}{l_\mathrm{m}A\rho}\left\{\frac{N_1}{RN_2}\frac{1}{n}\sum_{j=0}^{n-1}u_{1j}u_{2j} - \frac{1}{R_\mathrm{i}+R_2}\frac{1}{n}\sum_{j=0}^{n-1}u_{2j}^{\;2}\right\} \tag{B.8}$$

and the calculation of the specific apparent power follows:

$$S_\mathrm{s} = \frac{N_1}{l_\mathrm{m}RN_2 A\rho}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}u_{1j}^{\;2}}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}u_{2j}^{\;2}} \tag{B.9}$$

where

$B(t)$ is the magnetic flux density, in function of time, in teslas;

$H(t)$ is the magnetic field strength, in function of time, in amperes per metre;

$\hat{B}$ is the peak value of the magnetic flux density, in teslas;

$\hat{H}$ is the peak value of the magnetic field strength, in amperes per metre;

P_s is the specific total loss of the test specimen, in watts per kilogram;

S_s is the specific apparent power of the test specimen, in volt-amperes per kilogram;

T is the length of the period of the magnetization, in seconds;

f is the magnetizing frequency, in hertz;

f_s is the sampling frequency, in points per second;

l_m is the mean magnetic path length of the test specimen, in metres;

N_1 is the number of turns of the magnetizing winding;

N_2 is the number of turns of the secondary winding;

A is the cross-sectional area of the test specimen, in square metres;

ρ is the density of the material, in kilograms per cubic metre;

u_{1j} is the instantaneous value of the voltage across the non-inductive precision resistor, in volts;

u_{2j} is the instantaneous value of the induced secondary voltage, in volts;

n is the number of instantaneous values sampled over one period;

j is the index of instantaneous values;

$U_1(t)$ is the voltage across the non-inductive precision resistor, in function of time, in volts;

$U_2(\tau)$ is the induced secondary voltage, in function of time, in volts;

τ is an auxiliary time variable;

$\tilde{U}_2$ is the r.m.s. value of induced secondary voltage, in volts;

R is the resistance of the non-inductive precision resistor, in ohms;

R_i is the input resistance of the digitizer, in ohms;

R_2 is the resistance of the secondary winding, in ohms.

The pairs of numerical signals, $U_H(t)$ and $U_2(t)$, can then be processed by a computer or, for real time processing, a digital signal processor (DSP) using a sufficiently fast digital multiplier and adder without intermediate storage being required. Keeping the Nyquist condition is possible only where the sampling frequency f_s and the frequency f of the magnetization are derived from a common high frequency clock and thus have an integer ratio f_s/f. In that case, $U_1(t)$ and $U_2(t)$ may be scanned using 128 samples per period with sufficient accuracy (above 1 000 Hz, 64 samples per period may be sufficient). This figure is, according to the Shannon theorem, determined by the highest relevant frequency in the $H(t)$ signal, which is normally not higher than that of the 41st harmonic [7] in technical frequencies. However, some commercial data acquisition equipment cannot be synchronized with the frequency of the magnetization and, as a consequence, the ratio f_s/f is not an integer, i.e. the Nyquist condition is not met. In that case, the sampling frequency should be considerably higher (500 samples per period or more) in order to keep the deviation of the true period length from the nearest time of sampled point small. Keeping the Nyquist condition becomes a decisive advantage in the case of higher frequency applications to keep the sampling frequency reasonable low. The use of a low-pass anti-aliasing filter is recommended in order to eliminate irrelevant higher frequency components which would otherwise interact with the digital sampling process producing aliasing noise [2].

Regarding the amplitude resolution, studies found in the Bibliography have shown that below a 12-bit resolution, the digitization error can be considerable, particularly for non-oriented material with high silicon content [1, 7]. Thus, at least a 12-bit resolution of the given amplitude is recommended. Moreover, the two voltage channels should transfer the signals without a significant phase shift. A particularly significant condition in medium frequencies application is that the phase shift should be small enough so that the power measurement uncertainty specified in this standard, namely 0,5 %, is not exceeded. The consideration of the phase shift is more relevant the lower the power factor cos(φ) becomes (φ being the phase difference between the fundamental components of the two voltage signals). Signal conditioning amplifiers are preferably DC coupled to avoid any low frequency phase shift. However, DC offsets in the signal conditioning amplifiers can lead to significant errors in the numerically calculated values. Numerical correction cancelling can be applied to remove such DC offsets.

B.3 Calibration aspects

The verification of the reproducibility requirements of this document makes careful calibration of the measurement equipment necessary. The two voltage channels including preamplifiers and ADC can be calibrated using a calibrated reference voltage source traceable to national standards [6]. By connecting the reference AC voltage source to inputs of the two voltage channels, the amplitude of each channel and the phase difference between channels and the dependence on the frequency should be verified. These performances of the two channels can be taken into account with the evaluation processing in the computer. The phase shifts increase as the frequency increases. The phase shifts should be small enough so that the power measurement uncertainty meets the requirement of parties concerned. In any case, it would not be sufficient to calibrate the set-up using reference samples because that calibration would only be effective for that combination of material and measurement condition.

B.4 Numerical air flux compensation

In the case of the ring test, the test specimen is enclosed in an annular case, and the numerical air flux compensation can be achieved by the principle of the mutual inductor.

Firstly the voltage drop across the precision resister R_n (see Figure 3), $U_1(t)$, is differentiated in a way to avoid phase shifts and significant noise amplification injected from the current signal. A possible method is a five-point or twelve-point differentiation.

Secondly the compensation can be carried out as follows:

$$U_{2c}(t) = U_{2m}(t) - \frac{C}{R} \cdot \frac{dU_1(t)}{dt} \qquad \text{(B.10)}$$

where

$U_{2c}(t)$ is the compensated induced secondary voltage, in volts;

$U_{2m}(t)$ is the uncompensated induced secondary voltage, in volts;

C is the value of compensation factor in ohm seconds;

$U_1(t)$ is the voltage drop across the non-inductive precision resistor R_n (see Figure 3), in volts;

R is the resistance of the non-inductive precision resistor R_n, in ohms.

The adjustment of the value of compensation factor can be made so that, when passing an alternating current through the magnetizing windings in the absence of the specimen in the annular case, the compensated voltage shall be no more than 0,1 % of the non-compensated voltage appearing across the secondary winding of the annular case alone.

The numerical air flux compensation is advantageous to avoid increases in phase shift and impedance of windings caused by addition of mutual inductor.

Annex C
(informative)

Sinusoidal waveform control by digital means

The prescribed sinusoidal waveform of the induced secondary voltage can be difficult to achieve by means of conventional analogue feedback techniques at medium and high frequencies. Instabilities and auto-oscillations are in fact likely to occur when the frequency is increased beyond a few hundred hertz. The digital feedback method is, in principle, independent of frequency and is expected to be immune from auto-oscillatory effects [2]-[4].

In a possible realization of this method, it is assumed that the time functions $B(t)$ and $H(t)$ form a parametric representation of the hysteresis loop $B(H)$. Under this assumption, a certain time dependence of the current in the ~~primary~~ magnetizing circuit (i.e. $H(t)$) automatically defines the $B(t)$ function.

A computer controlled arbitrary waveform generator is employed to provide the required $H(t)$ function. An iterative procedure is devised, where at each i^{th} step the dynamic $B(H)$ relationship is refreshed by the actual $B_i(t)$ and $H_i(t)$ functions and is used to calculate the function $H_{i+1}(t)$ at the $(i+1)^{th}$ step. The iteration can be stopped once the prescribed form factor value 1,111 with a relative tolerance of ± 1 % of the induced secondary voltage is attained.

The so-calculated $H(t)$ function must be translated into a function ~~$V_g(t)$~~ $U_g(t)$ to be fed into the arbitrary waveform source. ~~$V_g(t)$~~ $U_g(t)$ can be related to $H(t)=\frac{N_1 I(t)}{\ell_m}$ by solving in the following way. If R_s denotes the total series resistance of the ~~primary~~ magnetizing circuit and G denotes the gain of the power amplifier, then the neglecting spurious capacitance effects:

$$U_g(t)=\frac{1}{G}\left(\frac{R_s H(t)\ell_m}{N_1}+N_1 A\frac{dB(t)}{dt}\right) \qquad \text{(C.1)}$$

where

$$\frac{dB(t)}{dt}=\omega\hat{B}\sin(\omega t) \qquad \text{(C.2)}$$

Based on the same principle, it is possible to define the associated function $B(t)$, for a given specimen, to a sinusoidal $H(t)$ waveform and correspondingly calculate the voltage function ~~$V_g(t)$~~ $U_g(t)$ to be fed into the source, in order to maintain a sinusoidal magnetizing current.

~~NOTE~~ If the effect of the air flux enclosed between the test specimen and the magnetizing winding cannot be disregarded, the additional term $U_{air}=\frac{1}{G}\mu_0 N_1(A'-A)\frac{dH(t)}{dt}$ ~~must~~ should be included in Formula (C.1).

Bibliography

~~IEC 62044 (all parts), *Cores made of soft magnetic materials – Measuring methods*~~

[1] DE WULF, M. and MELKEBEEK, J., On the advantage and drawbacks of using digital acquisition systems for the determination of magnetic properties of electrical steel sheet and strip. J. Magn. Magn. Mater., 196-197 (1999) p.940-942

[2] STERNS, S.D., Digital signal analysis. 5th Edition, Hayden Book (1991), ISBN: 0-8104-5828-4

[3] FIORILLO, F., Measurement and characterization of magnetic materials. Elsevier Series in Electromagnetism. Academic Press (2004), ISBN: 0-12-257251-3

[4] BERTOTTI, G., FERRARA, E., FIORILLO, F. and PASQUALE, M., Loss measurements on amorphous alloys under sinusoidal and distorted induction waveform using a digital feedback technique. Journal of Applied Physics, 73 (1993) p.5375-5377

[5] LÜDKE, J. and AHLERS, H., Hybrid control used to obtain sinusoidal curve form for the power loss measurement on magnetic materials. Proceedings of the EMMA Conference 2000: Materials Science Forum, 373-376 (2001) p.469-472

[6] AHLERS, H., Precision calibration procedure for magnetic loss testers using a digital two-channel function generator. SMM 11 Venice 1993, J. Magn. Magn. Mater., vol 133 (1994) p.437-439

[7] AHLERS, H. and SIEVERT, J., Uncertainties of Magnetic Loss Measurements, particularly in Digital Procedures. PTB-Mitt. 94 (1984) p.99-107

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Magnetic materials –
Part 6: Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to 100 kHz by the use of ring specimens

Matériaux magnétiques –
Partie 6: Méthodes de mesure des propriétés magnétiques des matériaux métalliques et des matériaux en poudre magnétiquement doux, aux fréquences comprises entre 20 Hz et 100 kHz, sur des éprouvettes en forme de tore

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

MAGNETIC MATERIALS –

Part 6: Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to 100 kHz by the use of ring specimens

FOREWORD

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International Standard IEC 60404-6 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

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

This edition includes the following significant technical changes with respect to the previous edition:

a) adaption to modern measurement and evaluation methods, in particular the introduction of the widely spread digital sampling method for the acquisition and evaluation of the measured data;

b) limitation of the frequency range up to 100 kHz;

c) deletion of Clause 7 of the second edition that specified the measurement of magnetic properties using a digital impedance bridge;

d) addition of a new Clause 7 on the measurement of the specific total loss by the wattmeter method, including an example of the application of the digital sampling method;

e) addition of an informative annex on the technical details of the digital sampling technique for the determination of magnetic properties.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
68/595/FDIS	68/600/RVD

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

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

A list of all parts in the IEC 60404 series, published under the general title *Magnetic materials*, can be found on the IEC website.

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

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

The contents of the corrigendum of November 2018 have been included in this copy.

MAGNETIC MATERIALS –

Part 6: Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to 100 kHz by the use of ring specimens

1 Scope

This part of IEC 60404 specifies methods for the measurement of AC magnetic properties of soft magnetic materials, other than electrical steels and soft ferrites, in the frequency range 20 Hz to 100 kHz. The materials covered by this part of IEC 60404 include those speciality alloys listed in IEC 60404-8-6, amorphous and nano-crystalline soft magnetic materials, pressed and sintered and metal injection moulded parts such as are listed in IEC 60404-8-9, cast parts and magnetically soft composite materials.

The object of this part is to define the general principles and the technical details of the measurement of the magnetic properties of magnetically soft materials by means of ring methods. For materials supplied in powder form, a ring test specimen is formed by the appropriate pressing method for that material.

The measurement of the DC magnetic properties of soft magnetic materials is made in accordance with the ring method of IEC 60404-4. The determinations of the magnetic characteristics of magnetically soft components are made in accordance with IEC 62044-3.

NOTE IEC 62044-3:2000 specifies methods for the measurement of AC magnetic characteristics of magnetically soft components in the frequency range up to 10 MHz.

Normally, the measurements are made at an ambient temperature of (23 ± 5) °C on test specimens which have first been magnetized, then demagnetized. Measurements can be made over other temperature ranges by agreement between parties concerned.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism*

IEC 60050-221, *International Electrotechnical Vocabulary – Chapter 221: Magnetic materials and components*

IEC 60404-2, *Magnetic materials – Part 2: Methods of measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame*

IEC 60404-4, *Magnetic materials – Part 4: Methods of measurement of d.c. magnetic properties of iron and steel*

IEC 60404-8-6, *Magnetic materials – Part 8-6: Specifications for individual materials – Soft magnetic metallic materials*

IEC 60404-8-9, *Magnetic materials – Part 8: Specifications for individual materials – Section 9: Standard specification for sintered soft magnetic materials*

IEC 62044-3, *Cores made of soft magnetic materials – Measuring methods – Part 3: Magnetic properties at high excitation level*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-121 and IEC 60050-221 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 General principles of measurement

4.1 Principle of the ring method

The measurements are made on a closed magnetic circuit in the form of a ring test specimen wound with two windings.

4.2 Test specimen

The test specimen shall be in the form of a ring of rectangular cross-section which may be formed by

a) winding thin strip or wire to produce a clock-spring wound toroidal core; or

b) a stack of punched, laser cut, wire cut or photochemically etched ring laminations; or

c) pressing and sintering of powders, metal injection moulding, 3D printing or casting.

In the case of powder materials, the production of a ring test specimen by metal injection moulding or by pressing (with heating if applicable) shall be carried out in accordance with the material manufacturer's recommendations to achieve the optimum magnetic performance of the powder material.

For all types of test specimen, burrs and sharp edges should be removed prior to heat treatment. It is preferable to enclose the test specimen in a two-part non-magnetic annular case. The case dimensions shall be such that it closely fits without introducing stress into the material of the test specimen.

The ring shall have dimensions such that the ratio of the outer to inner diameter shall be no greater than 1,4 and preferably less than 1,25 to achieve a sufficiently homogenous magnetization of the test specimen.

For solid and pressed powder materials, the dimensions of the test specimen, that is the outer and inner diameters and the height of the ring, shall be measured with suitable calibrated instruments. The respective dimensions shall be measured at several locations on a test specimen and averaged. The cross-sectional area of the test specimen shall be calculated from Formula (1).

$$A = \frac{(D - d)}{2} h \qquad (1)$$

where

A is the cross-sectional area of the test specimen, in square metres;

D is the outer diameter of the test specimen, in metres;

d is the inner diameter of the test specimen, in metres;

h is the height of the test specimen, in metres.

For a stack of laminations or a toroidal wound core, the cross-sectional area of the test specimen shall be calculated from the mass, density and the values of the inner and outer diameter of the ring specimen. The mass and diameters shall be measured with suitable calibrated instruments. The density shall be the conventional density for the material supplied by the manufacturer. The cross-sectional area shall be calculated from Formula (2).

$$A = \frac{2\,m}{\rho\pi\,(D + d)} \qquad (2)$$

where

m is the mass of the test specimen, in kilograms;

ρ is the density of the material, in kilograms per cubic metre.

For the calculation of the magnetic field strength, the mean magnetic path length of the test specimen determined from Formula (3) shall be used.

$$l_m = \pi \frac{(D + d)}{2} \qquad (3)$$

where

l_m is the mean magnetic path length of the test specimen, in metres.

NOTE For measurements of magnetically soft components, an effective core cross-sectional area and an effective magnetic path length are used (described in IEC 62044-3:2000). The difference in results between material measurements and component measurements is larger when the ratio of the outer to inner diameter is larger.

If the specific total loss is to be determined, the mass of the test specimen shall be measured with a suitable calibrated balance.

4.3 Windings

The test specimen shall be wound with a magnetizing winding and a secondary winding (see Annex A).

The numbers of turns depend upon the measuring equipment and method being used. The secondary winding shall be wound as closely as possible to the test specimen to minimize the effect of air flux enclosed between the test specimen and the secondary winding. All windings shall be wound uniformly over the whole length of the test specimen.

For measurements at frequencies above power frequencies, care shall be taken to avoid complications related to capacitance and other effects. These are introduced and discussed in Annex A.

Care shall be taken to ensure that the wire insulation is not damaged during the winding process causing a short circuit to the test specimen. An electrical check shall be made with a suitable AC insulation resistance measuring device to ensure that there is no direct connection between the windings and the test specimen.

5 Temperature measurements

When the temperature of the surface of the test specimen is required, it shall be measured by affixing a calibrated non-magnetic thermocouple (for example a type T thermocouple) to the test specimen. Where the test specimen is enclosed in an annular case, a small hole shall be made in the case, taking care not to damage the material of the test specimen, and the thermocouple fixed in contact with the test specimen. If this is not possible, the thermocouple shall be affixed to the case and this procedure shall be reported in the test report. The thermocouple shall be connected to a suitable calibrated voltmeter in order to measure its output voltage which can be related to the corresponding temperature through the calibration tables for the thermocouple.

Where the temperature of the test specimen is found to vary with time after magnetization, the measurements of the magnetic properties shall be carried out either when an agreed temperature is reached or after a time agreed between the parties concerned. If measurements are to be made at elevated temperatures, these may be carried out with the test specimen placed in a suitable oven to produce the required temperature.

A second smaller time-dependent magnetic relaxation effect can also affect the magnetic properties. For the types of materials covered by this document, the effect is usually masked by temperature changes. However, if such magnetic relaxation effects become apparent, then the test specimen should dwell at the prescribed magnetic flux density or magnetic field strength for an agreed period of time before making the final measurements.

6 Measurement of the relative amplitude permeability and the AC magnetization curve

6.1 General

The measurements are made using the ring method at frequencies normally from 20 Hz to 100 kHz, the upper frequency being limited by the performance of the instrumentation.

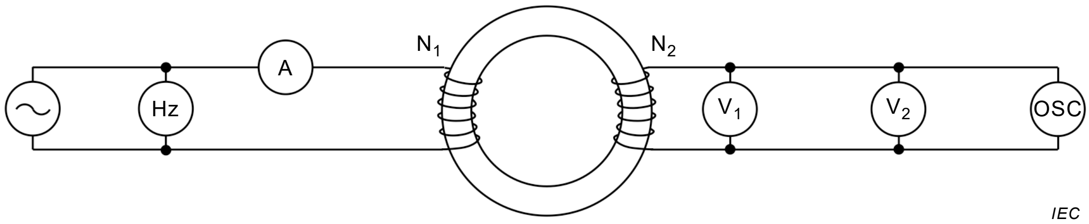
Where suitable calibrated instruments exist and careful winding to reduce interwinding capacitance has been performed, this upper limit may be extended to 1 MHz (See Annex A).

6.2 Apparatus and connections

The apparatus shall be connected as shown in Figure 1.

NOTE 1 Figure 3 can be used for the measurement of the relative amplitude permeability and the magnetization curve using the digital sampling technique.

NOTE 2 For the application of digital sampling technique, see Annex B.



Key

~	power supply (usually an oscillator and a power amplifier)
A	true r.m.s. or peak reading ammeter, or a true r.m.s. or peak reading voltmeter and a non-inductive precision resistor to measure the magnetizing current
Hz	frequency meter
N_1	magnetizing winding
N_2	secondary winding
OSC	oscilloscope
V_1	average type voltmeter
V_2	r.m.s. voltmeter

Figure 1 – Circuit of the measurement apparatus

When conducting sinusoidal current measurements, a non-inductive precision resistor should be connected in series with the magnetizing winding N_1 to guarantee that the magnetizing circuit resistance is at least ten times greater than the impedance of the magnetizing winding N_1 on the test specimen.

The source of alternating current shall have a variation of voltage and frequency at its output individually not exceeding ± 0,2 % of the adjusted value during the measurement. It shall be connected to a true r.m.s. or peak reading ammeter, or a true r.m.s. or peak reading voltmeter and a parallel non-inductive precision resistor, in series with the magnetizing winding N_1 on the test specimen, to measure the magnetizing current.

The secondary circuit comprises a secondary winding N_2 connected to two voltmeters in parallel. One voltmeter V_2 measures the true r.m.s. value, the other voltmeter V_1 measures the average rectified value but is sometimes scaled in values 1,111 times the rectified value.

The waveform of the induced secondary voltage that is induced in the secondary winding N_2 should be checked with an oscilloscope to ensure that only the fundamental component is present.

6.3 Waveform of induced secondary voltage or magnetizing current

In order to obtain comparable measurements, it shall be agreed prior to the measurements that either the waveform of the induced secondary voltage or the waveform of the magnetizing current shall be maintained sinusoidal with a form factor of 1,111 with a relative tolerance of ± 1 %. In the latter case, a non-inductive precision resistor connected in series with the magnetizing winding is required.

NOTE 1 The waveform of the induced secondary voltage and the magnetizing current can be measured by the digital sampling technique. See Figure 3 and Annex B.

The time constant of the non-inductive precision resistor should be checked to be low to ensure that the waveform is within the specified limits.

The non-inductive precision resistor may be the same resistor as used for the measurement of the magnetizing current.

NOTE 2 Sinusoidal waveform control can be achieved by digital means (see Annex C).

At frequencies in the range 20 Hz to 50 kHz, the form factor of the induced secondary voltage can be determined by connecting two voltmeters having a high impedance (typically > 1 MΩ in parallel with 90 pF to 150 pF) across the secondary winding. One voltmeter shall be responsive to the r.m.s. value of voltage and the other shall be responsive to the average rectified value of the voltage. The form factor is then determined from the ratio of the r.m.s. value to the average rectified value.

For optimum power transfer, it may be necessary to optimize the number of turns of the magnetizing winding to match the output impedance of the power supply. This can be determined from Formula (4).

$$Z = \mathrm{j}\omega L \tag{4}$$

where

Z is the output impedance of the power supply, in ohms;

j is the complex number sign;

ω is the angular frequency of the output of the power supply, in radians per second;

L is the effective inductance of the magnetizing winding of the test specimen, in henrys, calculated from Formula (5).

$$L = \frac{N_1^2 A \mu_0 \mu_r}{l_m} \tag{5}$$

where

N_1 is the number of turns of the magnetizing winding;

A is the cross-sectional area of the test specimen, in square metres;

μ_0 is the magnetic constant ($4\pi \times 10^{-7}$ henrys per metre);

μ_r is the relative amplitude permeability of the test specimen;

l_m is the mean magnetic path length of the test specimen, in metres.

Where the relative amplitude permeability is not known, a preliminary measurement may need to be made of the peak values of magnetic field strength and magnetic flux density as described in 6.4.1 and 6.4.2 and the relative amplitude permeability calculated as described in 6.4.3.

6.4 Determination of characteristics

6.4.1 Determination of the peak value of the magnetic field strength

The peak value of magnetic field strength at which the measurement is to be made is calculated from Formula (6).

$$\hat{H} = \frac{N_1 \hat{I}}{l_m} \tag{6}$$

where

$\hat{H}$ is the peak value of the magnetic field strength, in amperes per metre;

N_1 is the number of turns of the magnetizing winding on the test specimen;

$\hat{I}$ is the peak value of the magnetizing current, in amperes;

l_m is the mean magnetic path length of the test specimen, in metres.

Normally the amplitude of the magnetic field strength is determined by measuring the r.m.s. magnetizing current and multiplying by the square root of 2. For sinusoidal magnetizing current, this defines the correct value of the peak value of magnetic field strength. For sinusoidal magnetic flux density, this defines an equivalent peak value of magnetic field strength, which is numerically lower for a given magnetizing current. As an alternative, the peak value of magnetic field strength can be determined using a calibrated peak reading ammeter or a peak reading voltmeter and a non-inductive precision resistor.

Prior to measurement, the test specimen shall be carefully demagnetized from a value of field strength of not less than ten times the coercivity by slowly reducing the corresponding magnitude of the magnetizing current to zero. Demagnetization shall be carried out at the same or lower frequency as will be used for the measurements.

6.4.2 Determination of the peak value of the magnetic flux density

The average rectified value of the induced secondary voltage shall be measured using a calibrated average type voltmeter or a digitizer (see Figure 3), and the peak value of the magnetic flux density shall be calculated from Formula (7).

$$\hat{B} = \frac{1}{4 f N_2 A} \overline{|U_2|} \qquad (7)$$

where

$\hat{B}$ is the peak value of magnetic flux density, in teslas;

$\overline{|U_2|}$ is the average rectified value of the induced secondary voltage, in volts;

f is the frequency, in hertz;

A is the cross-sectional area of the test specimen, in square metres.

N_2 is the number of turns of the secondary winding.

NOTE For the application of the digital sampling technique, see Annex B.

Depending on the level of magnetic field strength and the ratio of the cross-sectional areas of the test specimen and the secondary winding, it may be necessary to make a correction to the magnetic flux density for the air flux enclosed between the test specimen and the secondary winding. The corrected value B of the magnetic flux density is given by Formula (8).

$$B = B' - \mu_0 H \frac{(A' - A)}{A} \qquad (8)$$

where

B' is the measured value of magnetic flux density, in teslas;

μ_0 is the magnetic constant ($4\ \pi \times 10^{-7}$ henrys per metre);

H is the magnetic field strength, in amperes per metre;

A' is the cross-sectional area enclosed by the secondary winding, in square metres;

A is the cross-sectional area of the test specimen, in square metres.

6.4.3 Determination of the r.m.s. amplitude permeability and the relative amplitude permeability

For corresponding peak values of magnetic field strength and magnetic flux density, the r.m.s. amplitude permeability shall be calculated from Formula (9).

$$\mu_{a,rms} = \frac{\hat{B}}{\mu_0 \sqrt{2}\, \widetilde{H}} \qquad (9)$$

where

$\mu_{a,rms}$ is the r.m.s. amplitude permeability;

μ_0 is the magnetic constant ($4\ \pi \times 10^{-7}$ henrys per metre);

$\hat{B}$ is the peak value of magnetic flux density, in teslas;

$\widetilde{H}$ is the r.m.s. value of magnetic field strength, in amperes per metre.

NOTE The relative amplitude permeability, μ_r, can be conventionally expressed as:

$$\mu_r = \frac{\hat{B}}{\mu_0 \hat{H}} \qquad (10)$$

where

μ_r is the relative amplitude permeability;

μ_0 is the magnetic constant ($4\ \pi \times 10^{-7}$ henrys per metre);

$\hat{B}$ is the peak value of magnetic flux density, in teslas;

$\hat{H}$ is the peak value of magnetic field strength, in amperes per metre.

6.4.4 Determination of the AC magnetization curve

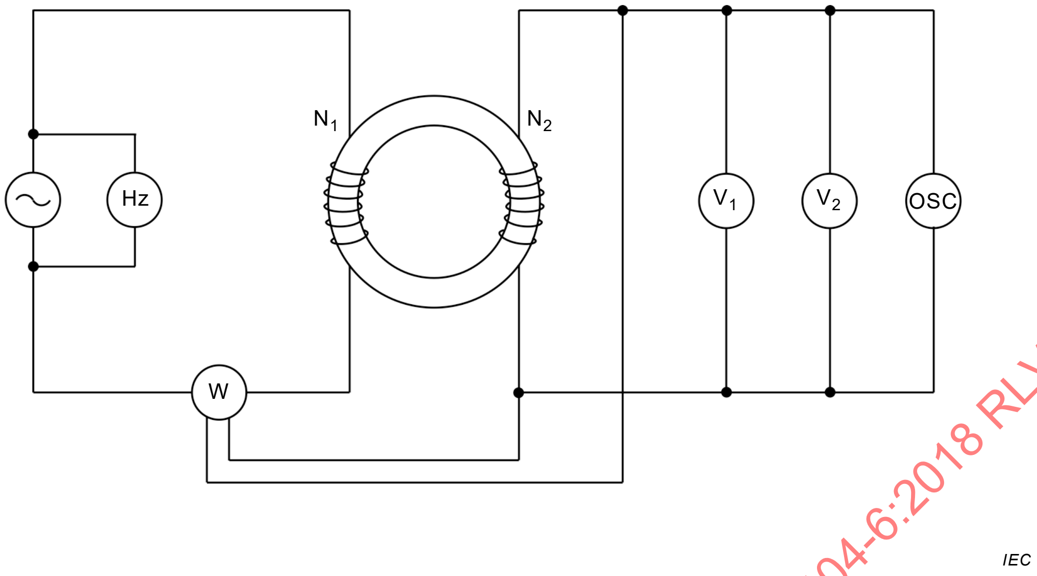
The test specimen shall be carefully demagnetized as described in 6.4.1. By successively increasing the magnetizing current, corresponding peak values of magnetic field strength and magnetic flux density can be obtained from which an AC magnetization curve can be plotted.

7 Measurement of the specific total loss by the wattmeter method

7.1 Principle of measurement

The principle of measurement is similar to that described in IEC 60404-2 except that the Epstein frame is replaced by the ring test specimen and the instrumentation is capable of making measurements at the required frequency. The measurement of specific total loss shall be done under conditions of sinusoidal magnetic flux density. For some test specimens, this may require the control of the induced secondary voltage waveform (see Annex C) by means of analogue or digital techniques to ensure that sinusoidal magnetic flux density is maintained.

The apparatus and the windings of the test specimen shall be connected as shown in Figure 2.



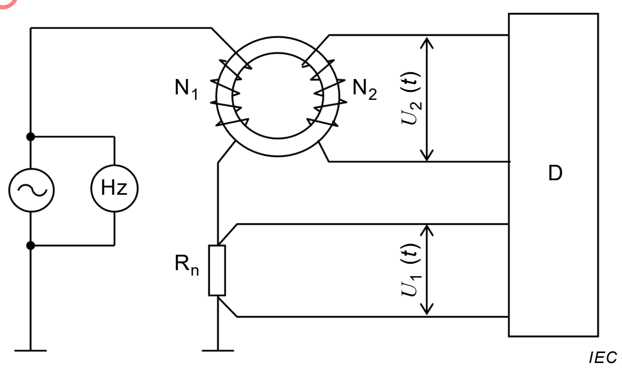
Key

~	power supply (usually an oscillator and amplifier)
Hz	frequency meter
N_1	magnetizing winding
N_2	secondary winding
OSC	oscilloscope
W	wattmeter
V_1	average type voltmeter
V_2	r.m.s. voltmeter

Figure 2 – Circuit of the conventional analogue wattmeter method (also representing the metrological principle of the digital wattmeter method)

For the digital sampling technique, Figure 3 shows a possible circuit structure as an example. In the latter case, a digitizer and supporting software adopt the functions of the oscilloscope, the wattmeter and the voltmeters shown in Figure 2.

NOTE Figure 3 is not the only possible structure of digital sampling technique application, see Annex B.



Key

R_n	non-inductive precision resistor in series with the magnetizing winding to determine the magnetizing current
D	digitizer (usually a digital power analyser or a digital acquisition system with a computer)

Figure 3 – The wattmeter method when connected with the digital sampling technique (example of circuit)

7.2 Voltage measurement

7.2.1 Average type voltmeter

The average rectified value of the induced secondary voltage shall be measured using a calibrated average type voltmeter or a calibrated digitizer (see Figures 2 and 3). The load on the secondary circuit shall be as low as possible (see Annex A). Consequently a digital voltmeter or digitizer with high input impedance is required.

NOTE 1 Average type voltmeters are usually graduated in average rectified value multiplied by 1,111.

NOTE 2 For the application of digital sampling technique, see Annex B.

7.2.2 R.M.S. type voltmeter

The true r.m.s. value of the induced secondary voltage shall be measured using a calibrated voltmeter responsive to r.m.s. values or a calibrated digitizer (see Figures 2 and 3). The load on the secondary circuit shall be as low as possible (see Annex A). Consequently a digital voltmeter or digitizer with high input impedance is required.

NOTE For the application of digital sampling technique, see Annex B.

7.3 Power measurement

The power shall be measured using a calibrated wattmeter suitable for circuits which may have a low power factor ($\cos\phi$ down to 0,1) or a calibrated digitizer (see Figures 2 and 3). The input impedance of the voltage circuit shall be as high as possible (see Annex A).

NOTE For the application of digital sampling technique, see Annex B.

7.4 Procedure for the measurement of the specific total loss

The test specimen shall be carefully demagnetized as described in 6.4.1. The current in the magnetizing winding shall be increased until the average rectified voltage corresponds to the required peak value of magnetic flux density calculated from Formula (7).

The average rectified value and the r.m.s. value of the induced secondary voltage shall be recorded and the form factor of the secondary waveform shall be calculated and verified in accordance with 6.2. The wattmeter reading shall then be recorded.

NOTE For the application of digitizing methods, see Annex B.

7.5 Determination of the specific total loss

The power P_m measured by the wattmeter includes the power consumed by the instruments in the secondary circuit, which to a first approximation is equal to $\tilde{U}_2^{\,2} / R_i$, since the induced secondary voltage is essentially sinusoidal.

Thus, the total loss P_c of the test specimen shall be calculated in accordance with Formula (11).

$$P_c = \frac{N_1}{N_2} P_m - \frac{\tilde{U}_2^{\,2}}{R_i} \qquad (11)$$

where

P_c is the calculated total loss of the test specimen, in watts;

P_m is the power measured by the wattmeter, in watts;

N_1 is the number of turns of the magnetizing winding;

N_2 is the number of turns of the secondary winding;

$\tilde{U}_2$ is the r.m.s. value of the induced secondary voltage, in volts;

R_i is the combined equivalent resistance of the instruments connected to the secondary winding, in ohms.

The specific total loss P_s shall be obtained by dividing P_c by the mass of the test specimen. Hence,

$$P_s = \frac{P_c}{m} \tag{12}$$

where

P_s is the specific total loss of the test specimen, in watts per kilogram;

m is the mass of the test specimen, in kilograms.

8 Uncertainties

The individual contributions to the uncertainty of a particular measurement shall be identified and then combined in accordance with the guidelines set out in ISO/IEC Guide 98-3 to the expression of uncertainty in measurement.

9 Test report

The test report shall contain as necessary

a) the type and serial number or mark of the test specimen;

b) the number of turns of the magnetizing winding and the secondary winding on the test specimen;

c) the mass and dimensions of the test specimen and, for thin material, the density;

d) the frequency;

e) the test method used;

f) the ambient temperature;

g) the surface temperature of the test specimen;

h) the method for determining the peak value of the flux density;

i) the nature of the waveform: sinewave of induced secondary voltage or sinewave of magnetizing current;

j) the method for determining the peak value of magnetizing current;

k) the quantities measured and their uncertainties.

Annex A
(informative)

Guidance on requirements for windings and instrumentation in order to minimise additional losses

A.1 General

At frequencies above power frequencies, additional losses associated with the windings on the test specimen can occur. These arise from

a) the interwinding capacitance between the magnetizing and secondary windings on the test specimen;
b) the capacitance of the leads from the secondary winding to the instruments;
c) the capacitance and resistance of the input circuits of the instruments; and
d) the dielectric loss of the insulating material of the secondary winding.

A.2 Reduction of additional losses

The magnitude of the additional losses can be minimised by careful choice of winding wire, winding technique and instrumentation.

Wire insulated with a material having a low dielectric loss, for instance polytetrafluorethylene (PTFE) or polyethylene, should be used to minimise the effect of dielectric loss.

Where possible, the magnetizing and secondary windings should be separated to reduce the interwinding capacitance.

The connecting leads from the secondary winding to the instruments should have low dielectric loss insulation and should be kept as short as practicable.

The instruments should have a low input capacitance and high input resistance to avoid loading the secondary circuit.

Annex B
(informative)

Digital sampling technique for the determination of magnetic properties and numerical air flux compensation

B.1 General

The digital sampling technique is an advanced technique that is almost exclusively applied to the electrical part of the measurement procedure of this document. Applied to the wattmeter method, it is characterized by the digitization of the induced secondary voltage $U_2(t)$ and the voltage drop $U_1(t)$ across the non-inductive precision resistor in series with the magnetizing winding and by the evaluation of these data for the determination of the magnetic properties of the test specimen (see Figure 3).

For this purpose, instantaneous values of these voltages, having index j, u_2j and u_1j respectively, are sampled and held simultaneously from the time-dependent voltage signals during a narrow and equidistant time period each by sample-and-hold circuits. They are then immediately converted to digital values by analogue-to-digital converters (ADC). The data pairs sampled over one or more periods together with the test specimen data and the set-up parameters, provide the complete information for one measurement. This data set enables computer processing for the determination of all magnetic properties required in this document.

Whilst the digital sampling technique has perfectly proved its worth applied with the technical frequency range, it is expected that it will be effectively applicable to medium frequencies, i.e. that it can be applied to the measurement procedures which are described in the main part of this document. This expectation is based on the recent availability of fast sample-and-hold electronics. The circuit in Figure 2 applies equally to the analogue methods and the digital sampling technique; the digital sampling technique shown schematically in Figure 3 allows all functions of the measurement equipment shown in Figure 1 and Figure 2 to be realized by a combined system of a data acquisition equipment and software. The control of the sinusoidal waveform of the induced secondary voltage can also be realized by a digital method. However, the purpose and procedure of this technique are different from those of this annex and are treated in Annex C.

Annex B is helpful in understanding the impact of the digital sampling technique on the accuracy achievable by the methods of this document. This is particularly important because ADC circuits, transient recorders and supporting software are readily available and make it possible to establish a sampling wattmeter. The digital sampling technique can offer low uncertainty, but it leads to large errors if improperly used.

NOTE This principle and implementation of digital sampling technique are widely described in many papers and books (IEC 62044-3, [1] and [2][1]).

B.2 Technical details and requirements

The principle of the digital sampling technique is the discretization of voltage and time, i.e. the replacement of the infinitesimal time interval dt by the finite time interval Δt:

$$\Delta t = \frac{T}{n} = \frac{1}{f \cdot n} = \frac{1}{f_s} \tag{B.1}$$

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

where:

Δt is the time interval between the sampled points, in seconds;

T is the length of the period of the magnetization, in seconds;

n is the number of instantaneous values sampled over one period;

f is the frequency of the magnetization, in hertz;

f_s is the sampling frequency, in points per second.

In order to achieve lower uncertainties, the length of the period of the magnetization divided by the time interval between the sampled points, i.e. the ratio f_s/f, should be an integer (Nyquist condition [2]) and the sampling frequency, f_s, should be greater than twice the input signal bandwidth.

NOTE If the Nyquist condition is not met, i.e. if the sampling clock and the clock of the signal generator are not synchronized (see paragraph after the next one and paragraph before the last one of B2), the loss of accuracy can be compensated by an increase of the sampling frequency by a factor of at least 5.

The windings of the test specimen are connected with the digital components of the apparatus as shown in Figure 3.

The power supply is usually a computer controlled digital signal generator and a power amplifier. A low pass filter should be inserted between the digital signal generator and the power amplifier to prevent aliasing at the digitizer. The digitizer is usually a calibrated digital power analyzer or a calibrated digital acquisition system with a computer. The digitizer should have a high input impedance (typically >1 MΩ in parallel with 90 pF to 150 pF) to avoid loading the secondary circuit. It is recommended that the sampling clock of the digitizer should be synchronized with the clock of the digital signal generator (Nyquist condition).

The digitizer digitizes the voltage across the non-inductive precision resister and the voltage induced in the secondary winding simultaneously into instantaneous values u_{m1j} and u_{m2j} respectively. The values u_{m1j} and u_{m2j} should be corrected by the factor $\frac{R_i + R}{R_i}$ and $\frac{R_i + R_2}{R_i}$, respectively, to compensate for the voltage drop through the resistances of the instruments in the measuring circuit. Therefore, the values are calculated as follows:

$$u_{1j} = \frac{R_i + R}{R_i} u_{m1j} \qquad \text{(B.2)}$$

$$u_{2j} = \frac{R_i + R_2}{R_i} u_{m2j} \qquad \text{(B.3)}$$

where

u_{m1j} is the measured instantaneous value of the voltage across the non-inductive precision resister, in volts;

u_{m2j} is the measured instantaneous value of the voltage induced in the secondary winding, in volts;

u_{1j} is the instantaneous value of the voltage across the non-inductive precision resister, in volts;

u_{2j} is the instantaneous value of the voltage induced in the secondary winding, in volts;

R_i is the input resistance of the digitizer, in ohms;

R is the resistance of the non-inductive precision resistor, in ohms;

R_2 is the resistance of the secondary windings, in ohms.

A computer reconstructs the data arrays of u_{1j} and u_{2j} into numerical signals of voltages $U_1(t)$ and $U_2(t)$, respectively, over one period of magnetization.

Compensation of the effect of air flux on the induced secondary voltage $U_2(t)$ should be achieved by the numerical air flux compensation method (see Clause B.4).

The magnetic flux density $B(t)$ can be calculated by using

$$B(t) = \frac{1}{N_2 A}\left\{\int_0^t U_2(\tau)\mathrm{d}\,\tau - \frac{1}{T}\int_0^T\left(\int_0^t U_2(\tau)\mathrm{d}\,\tau\right)\mathrm{d}\,t\right\} \tag{B.4}$$

The second term in the brackets of Formula (B.4) is the time average over the length of a period which compensates for the integration constant.

The magnetic field strength $H(t)$ can be calculated by using:

$$H(t) = \frac{N_1}{Rl_\mathrm{m}}U_1(t) \tag{B.5}$$

According to an average-sensing voltmeter, the peak value of the flux density can be calculated by the sum of the u_{2j} values sampled over one period as follows:

$$\hat{B} = \frac{1}{4fN_2 A}\frac{1}{T}\int_{t=0}^{T}\left|U_2(t)\right|\mathrm{d}t \cong \frac{1}{4f_\mathrm{s}N_2 A}\sum_{j=0}^{n-1}\left|u_{2j}\right| \tag{B.6}$$

The peak value of the magnetic field strength can be calculated by using:

$$\hat{H} = \frac{N_1}{Rl_\mathrm{m}}\hat{U}_1 \tag{B.7}$$

The calculation of the specific total loss P_s can be carried out by point-by-point multiplication of the u_{1j} and u_{2j} values and summation over one period as follows:

$$P_\mathrm{s} = \frac{1}{l_\mathrm{m}A\rho}\left\{\frac{N_1}{RN_2}\frac{1}{T}\int_{t=0}^{T}U_1(t)U_2(t)\mathrm{d}t - \frac{\tilde{U}_2^{\,2}}{R_\mathrm{i}+R_2}\right\} \cong \frac{1}{l_\mathrm{m}A\rho}\left\{\frac{N_1}{RN_2}\frac{1}{n}\sum_{j=0}^{n-1}u_{1j}u_{2j} - \frac{1}{R_\mathrm{i}+R_2}\frac{1}{n}\sum_{j=0}^{n-1}u_{2j}^{\,2}\right\} \tag{B.8}$$

and the calculation of the specific apparent power follows:

$$S_\mathrm{s} = \frac{N_1}{l_\mathrm{m}RN_2 A\rho}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}u_{1j}^{\,2}}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}u_{2j}^{\,2}} \tag{B.9}$$

where

$B(t)$ is the magnetic flux density, in function of time, in teslas;

$H(t)$ is the magnetic field strength, in function of time, in amperes per metre;

$\hat{B}$ is the peak value of the magnetic flux density, in teslas;

$\hat{H}$ is the peak value of the magnetic field strength, in amperes per metre;

P_s is the specific total loss of the test specimen, in watts per kilogram;

S_s is the specific apparent power of the test specimen, in volt-amperes per kilogram;

T is the length of the period of the magnetization, in seconds;

f is the magnetizing frequency, in hertz;

f_s is the sampling frequency, in points per second;

l_m is the mean magnetic path length of the test specimen, in metres;

N_1 is the number of turns of the magnetizing winding;

N_2 is the number of turns of the secondary winding;

A is the cross-sectional area of the test specimen, in square metres;

ρ is the density of the material, in kilograms per cubic metre;

u_{1j} is the instantaneous value of the voltage across the non-inductive precision resistor, in volts;

u_{2j} is the instantaneous value of the induced secondary voltage, in volts;

n is the number of instantaneous values sampled over one period;

j is the index of instantaneous values;

$U_1(t)$ is the voltage across the non-inductive precision resistor, in function of time, in volts;

$U_2(\tau)$ is the induced secondary voltage, in function of time, in volts;

τ is an auxiliary time variable;

$\tilde{U}_2$ is the r.m.s. value of induced secondary voltage, in volts;

R is the resistance of the non-inductive precision resistor, in ohms;

R_i is the input resistance of the digitizer, in ohms;

R_2 is the resistance of the secondary winding, in ohms.

The pairs of numerical signals, $U_H(t)$ and $U_2(t)$, can then be processed by a computer or, for real time processing, a digital signal processor (DSP) using a sufficiently fast digital multiplier and adder without intermediate storage being required. Keeping the Nyquist condition is possible only where the sampling frequency f_s and the frequency f of the magnetization are derived from a common high frequency clock and thus have an integer ratio f_s/f. In that case, $U_1(t)$ and $U_2(t)$ may be scanned using 128 samples per period with sufficient accuracy (above 1 000 Hz, 64 samples per period may be sufficient). This figure is, according to the Shannon theorem, determined by the highest relevant frequency in the $H(t)$ signal, which is normally not higher than that of the 41st harmonic [7] in technical frequencies. However, some commercial data acquisition equipment cannot be synchronized with the frequency of the magnetization and, as a consequence, the ratio f_s/f is not an integer, i.e. the Nyquist condition is not met. In that case, the sampling frequency should be considerably higher (500 samples per period or more) in order to keep the deviation of the true period length from the nearest time of sampled point small. Keeping the Nyquist condition becomes a decisive advantage in the case of higher frequency applications to keep the sampling frequency reasonable low. The use of a low-pass anti-aliasing filter is recommended in order to eliminate irrelevant higher frequency components which would otherwise interact with the digital sampling process producing aliasing noise [2].

Regarding the amplitude resolution, studies found in the Bibliography have shown that below a 12-bit resolution, the digitization error can be considerable, particularly for non-oriented material with high silicon content [1, 7]. Thus, at least a 12-bit resolution of the given amplitude is recommended. Moreover, the two voltage channels should transfer the signals without a significant phase shift. A particularly significant condition in medium frequencies application is that the phase shift should be small enough so that the power measurement uncertainty specified in this standard, namely 0,5 %, is not exceeded. The consideration of the phase shift is more relevant the lower the power factor cos(φ) becomes (φ being the phase difference between the fundamental components of the two voltage signals). Signal conditioning amplifiers are preferably DC coupled to avoid any low frequency phase shift. However, DC offsets in the signal conditioning amplifiers can lead to significant errors in the numerically calculated values. Numerical correction cancelling can be applied to remove such DC offsets.

B.3 Calibration aspects

The verification of the reproducibility requirements of this document makes careful calibration of the measurement equipment necessary. The two voltage channels including preamplifiers and ADC can be calibrated using a calibrated reference voltage source traceable to national standards [6]. By connecting the reference AC voltage source to inputs of the two voltage channels, the amplitude of each channel and the phase difference between channels and the dependence on the frequency should be verified. These performances of the two channels can be taken into account with the evaluation processing in the computer. The phase shifts increase as the frequency increases. The phase shifts should be small enough so that the power measurement uncertainty meets the requirement of parties concerned. In any case, it would not be sufficient to calibrate the set-up using reference samples because that calibration would only be effective for that combination of material and measurement condition.

B.4 Numerical air flux compensation

In the case of the ring test, the test specimen is enclosed in an annular case, and the numerical air flux compensation can be achieved by the principle of the mutual inductor.

Firstly the voltage drop across the precision resister R_n (see Figure 3), $U_1(t)$, is differentiated in a way to avoid phase shifts and significant noise amplification injected from the current signal. A possible method is a five-point or twelve-point differentiation.

Secondly the compensation can be carried out as follows:

$$U_{2c}(t) = U_{2m}(t) - \frac{C}{R} \cdot \frac{dU_1(t)}{dt} \tag{B.10}$$

where

$U_{2c}(t)$ is the compensated induced secondary voltage, in volts;

$U_{2m}(t)$ is the uncompensated induced secondary voltage, in volts;

C is the value of compensation factor in ohm seconds;

$U_1(t)$ is the voltage drop across the non-inductive precision resistor R_n (see Figure 3), in volts;

R is the resistance of the non-inductive precision resistor R_n, in ohms.

The adjustment of the value of compensation factor can be made so that, when passing an alternating current through the magnetizing windings in the absence of the specimen in the annular case, the compensated voltage shall be no more than 0,1 % of the non-compensated voltage appearing across the secondary winding of the annular case alone.

The numerical air flux compensation is advantageous to avoid increases in phase shift and impedance of windings caused by addition of mutual inductor.

Annex C
(informative)

Sinusoidal waveform control by digital means

The prescribed sinusoidal waveform of the induced secondary voltage can be difficult to achieve by means of conventional analogue feedback techniques at medium and high frequencies. Instabilities and auto-oscillations are in fact likely to occur when the frequency is increased beyond a few hundred hertz. The digital feedback method is, in principle, independent of frequency and is expected to be immune from auto-oscillatory effects [2]-[4].

In a possible realization of this method, it is assumed that the time functions $B(t)$ and $H(t)$ form a parametric representation of the hysteresis loop $B(H)$. Under this assumption, a certain time dependence of the current in the magnetizing circuit (i.e. $H(t)$) automatically defines the $B(t)$ function.

A computer controlled arbitrary waveform generator is employed to provide the required $H(t)$ function. An iterative procedure is devised, where at each i^{th} step the dynamic $B(H)$ relationship is refreshed by the actual $B_i(t)$ and $H_i(t)$ functions and is used to calculate the function $H_{i+1}(t)$ at the $(i+1)^{\text{th}}$ step. The iteration can be stopped once the prescribed form factor value 1,111 with a relative tolerance of ± 1 % of the induced secondary voltage is attained.

The so-calculated $H(t)$ function must be translated into a function $U_g(t)$ to be fed into the arbitrary waveform source. $U_g(t)$ can be related to $H(t) = \frac{N_1 I(t)}{\ell_m}$ by solving in the following way.

If R_s denotes the total series resistance of the magnetizing circuit and G denotes the gain of the power amplifier, then the neglecting spurious capacitance effects:

$$U_g(t) = \frac{1}{G}\left(\frac{R_s H(t)\ell_m}{N_1} + N_1 A \frac{dB(t)}{dt}\right) \quad \text{(C.1)}$$

where

$$\frac{dB(t)}{dt} = \omega \hat{B} \sin(\omega t) \quad \text{(C.2)}$$

Based on the same principle, it is possible to define the associated function $B(t)$, for a given specimen, to a sinusoidal $H(t)$ waveform and correspondingly calculate the voltage function $U_g(t)$ to be fed into the source, in order to maintain a sinusoidal magnetizing current.

If the effect of the air flux enclosed between the test specimen and the magnetizing winding cannot be disregarded, the additional term $U_{air} = \frac{1}{G}\mu_0 N_1 (A' - A)\frac{dH(t)}{dt}$ should be included in Formula (C.1).

Bibliography

[1] DE WULF, M. and MELKEBEEK, J., *On the advantage and drawbacks of using digital acquisition systems for the determination of magnetic properties of electrical steel sheet and strip*. J. Magn. Magn. Mater., 196-197 (1999) p.940-942

[2] STERNS, S.D., *Digital signal analysis*. 5th Edition, Hayden Book (1991), ISBN: 0-8104-5828-4

[3] FIORILLO, F., *Measurement and characterization of magnetic materials*. Elsevier Series in Electromagnetism. Academic Press (2004), ISBN: 0-12-257251-3

[4] BERTOTTI, G., FERRARA, E., FIORILLO, F. and PASQUALE, M., *Loss measurements on amorphous alloys under sinusoidal and distorted induction waveform using a digital feedback technique.* Journal of Applied Physics, 73 (1993) p.5375-5377

[5] LÜDKE, J. and AHLERS, H., *Hybrid control used to obtain sinusoidal curve form for the power loss measurement on magnetic materials.* Proceedings of the EMMA Conference 2000: Materials Science Forum, 373-376 (2001) p.469-472

[6] AHLERS, H., *Precision calibration procedure for magnetic loss testers using a digital two-channel function generator*. SMM 11 Venice 1993, J. Magn. Magn. Mater., vol 133 (1994) p.437-439

[7] AHLERS, H. and SIEVERT, J., *Uncertainties of Magnetic Loss Measurements, particularly in Digital Procedures*. PTB-Mitt. 94 (1984) p.99-107

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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MATÉRIAUX MAGNÉTIQUES –

Partie 6: Méthodes de mesure des propriétés magnétiques des matériaux métalliques et des matériaux en poudre magnétiquement doux, aux fréquences comprises entre 20 Hz et 100 kHz, sur des éprouvettes en forme de tore

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La Norme internationale IEC 60404-6 a été établie par le comité d'études 68 de l'IEC: Matériaux magnétiques tels qu'alliages et aciers.

Cette troisième édition annule et remplace la deuxième édition parue en 2003. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) adaptation aux méthodes modernes de mesure et d'évaluation, notamment l'introduction de la méthode d'échantillonnage numérique largement répandue pour l'acquisition et l'évaluation des données mesurées;
b) limitation de la gamme de fréquences à 100 kHz;
c) suppression de l'Article 7 de la deuxième édition qui spécifiait la mesure des propriétés magnétiques à l'aide d'un pont d'impédance numérique;
d) ajout d'un nouvel Article 7 sur la mesure des pertes totales massiques par la méthode du wattmètre, y compris un exemple d'application de la méthode d'échantillonnage numérique;
e) ajout d'une annexe informative concernant les détails de la technique d'échantillonnage numérique pour déterminer les propriétés magnétiques du matériau.

Le texte de cette Norme internationale est issu des documents suivants:

FDIS	Rapport de vote
68/595/FDIS	68/600/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de la présente Norme internationale.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2.

Une liste de toutes les parties de la série IEC 60404, publiées sous le titre général *Matériaux magnétiques*, peut être consultée sur le site web de l'IEC.

Le comité a décidé que le contenu de ce document ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous "http://webstore.iec.ch" dans les données relatives au document recherché. A cette date, le document sera

- reconduit,
- supprimé,
- remplacé par une édition révisée, ou
- amendé.

Le contenu du corrigendum de novembre 2018 a été pris en considération dans cet exemplaire.

MATÉRIAUX MAGNÉTIQUES –

Partie 6: Méthodes de mesure des propriétés magnétiques des matériaux métalliques et des matériaux en poudre magnétiquement doux, aux fréquences comprises entre 20 Hz et 100 kHz, sur des éprouvettes en forme de tore

1 Domaine d'application

La présente partie de l'IEC 60404 spécifie les méthodes à utiliser pour mesurer les propriétés magnétiques en courant alternatif des matériaux magnétiques doux autres que les aciers électriques et les ferrites doux, aux fréquences comprises entre 20 Hz et 100 kHz. Les matériaux couverts par la présente partie de l'IEC 60404 incluent les alliages de spécialité répertoriés dans l'IEC 60404-8-6, les matériaux magnétiques doux amorphes et nanocristallins, les pièces compressées frittées et les pièces moulées par injection de métal répertoriées dans l'IEC 60404-8-9, ainsi que les pièces moulées et les matériaux composites magnétiquement doux.

L'objet de la présente partie est de définir les principes généraux et les détails techniques de la mesure des propriétés magnétiques des matériaux magnétiquement doux au moyen des méthodes du tore. Pour les matériaux livrés sous forme de poudre, une éprouvette d'essai en forme d'anneau est réalisée à l'aide de la méthode de compression appropriée pour le matériau considéré.

La mesure des propriétés magnétiques en courant continu des matériaux magnétiquement doux est réalisée selon la méthode du tore de l'IEC 60404-4. Les déterminations des propriétés magnétiques des composants magnétiquement doux sont réalisées selon l'IEC 62044-3.

NOTE L'IEC 62044-3:2000 spécifie les méthodes à utiliser pour mesurer les propriétés magnétiques en courant alternatif des composants magnétiquement doux, aux fréquences allant jusqu'à 10 MHz.

Normalement, les mesures sont réalisées à une température ambiante de (23 ± 5) °C sur des éprouvettes d'essai qui ont été dans un premier temps aimantées, puis désaimantées. Des mesures peuvent être réalisées pour d'autres plages de températures, sous réserve d'un accord entre les parties concernées.

2 Références normatives

Les documents suivants cités dans le texte constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60050-121, *Vocabulaire Electrotechnique International – Partie 121: Electromagnétisme*

IEC 60050-221, *Vocabulaire Electrotechnique International – Chapitre 221: Matériaux et composants magnétiques*

IEC 60404-2, *Matériaux magnétiques – Partie 2: Méthodes de mesure des propriétés magnétiques des tôles et bandes magnétiques en acier au moyen d'un cadre Epstein*

IEC 60404-4, *Matériaux magnétiques – Partie 4: Méthodes de mesure en courant continu des propriétés magnétiques du fer et de l'acier*

IEC 60404-8-6, *Matériaux magnétiques – Partie 8-6: Spécifications pour matériaux particuliers — Matériaux métalliques magnétiquement doux*

IEC 60404-8-9, *Matériaux magnétiques – Partie 8: Spécifications pour matériaux particuliers – Section 9: Spécification des matériaux magnétiques doux frittés*

IEC 62044-3:2000, *Noyaux en matériaux magnétiques doux – Méthodes de mesure – Partie 3: Propriétés magnétiques à niveau élevé d'excitation*

ISO/IEC Guide 98-3, *Incertitude de mesure – Partie 3: Guide pour l'expression de l'incertitude de mesure (GUM:1995)*

3 Termes et définitions

Pour les besoins du présent document, les termes et les définitions de l'IEC 60050-121 et de l'IEC 60050-221 s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

4 Principes généraux de mesure

4.1 Principe de la méthode du tore

Les mesures sont réalisées sur un circuit magnétique fermé constitué d'une éprouvette d'essai en forme d'anneau entourée par deux enroulements.

4.2 Eprouvette d'essai

L'éprouvette d'essai doit avoir la forme d'un anneau de section droite rectangulaire qui peut être constitué par:

a) enroulement d'une bande mince ou d'un fil fin pour fabriquer un tore enroulé comme un ressort spiral d'horlogerie; ou par
b) une pile d'anneaux laminés, poinçonnés, découpés au laser, par électroérosion ou par usinage photochimique; ou par
c) compression et frittage de poudres, moulage par injection de métal, impression 3D ou coulée.

Dans le cas des matériaux en poudre, la confection d'une éprouvette d'essai en forme d'anneau par moulage par injection de métal ou par compression (avec chauffage, le cas échéant) doit être réalisée conformément aux recommandations du fabricant du matériau pour obtenir la performance magnétique optimale du matériau en poudre.

Pour tous les types d'éprouvettes d'essai, il convient d'éliminer les bavures et les arêtes vives avant le traitement thermique. Il est préférable d'insérer l'éprouvette d'essai dans un boîtier annulaire non magnétique en deux parties. Les dimensions du boîtier doivent être telles que le boîtier s'ajuste parfaitement sans introduire de contrainte dans le matériau de l'éprouvette d'essai.

L'anneau doit posséder des dimensions telles que le rapport du diamètre extérieur au diamètre intérieur ne soit pas supérieur à 1,4 et soit, de préférence, inférieur à 1,25, afin d'obtenir une aimantation de l'éprouvette d'essai suffisamment homogène.

Pour les matériaux solides et les matériaux en poudre compressés, les dimensions de l'éprouvette d'essai, c'est-à-dire les diamètres intérieur et extérieur et la hauteur de l'anneau, doivent être mesurées avec des instruments de mesure étalonnés appropriés. Ces dimensions doivent être mesurées en plusieurs endroits de l'éprouvette d'essai et ensuite être moyennées. La section de l'éprouvette d'essai doit être calculée à l'aide de la Formule (1).

$$A = \frac{(D-d)}{2} h \quad (1)$$

où

A est la section de l'éprouvette d'essai, en mètres carrés;

D est le diamètre extérieur de l'éprouvette d'essai, en mètres;

d est le diamètre intérieur de l'éprouvette d'essai, en mètres;

h est la hauteur de l'éprouvette d'essai, en mètres.

Pour un empilage de tôles ou un tore enroulé, la section de l'éprouvette d'essai doit être calculée à partir de la masse, de la masse volumique et des valeurs des diamètres intérieur et extérieur de l'éprouvette en forme de tore. La masse et les diamètres doivent être mesurés avec des instruments étalonnés appropriés. La masse volumique doit être la masse volumique conventionnelle du matériau fourni par le fabricant. La section doit être calculée à l'aide de la Formule (2).

$$A = \frac{2\,m}{\rho \pi (D+d)} \quad (2)$$

où

m est la masse de l'éprouvette d'essai, en kilogrammes;

ρ est la masse volumique du matériau, en kilogrammes par mètre cube.

Pour le calcul du champ magnétique, la longueur moyenne du circuit magnétique de l'éprouvette d'essai déterminée à l'aide de la Formule (3) doit être utilisée.

$$l_m = \pi \frac{(D+d)}{2} \quad (3)$$

où

l_m est la longueur moyenne du circuit magnétique de l'éprouvette d'essai, en mètres.

NOTE Pour les mesures de composants magnétiquement doux, une aire efficace de section droite du noyau et une longueur efficace du circuit magnétique sont utilisées (décrites dans l'IEC 62044-3:2000). La différence de résultats entre les mesures du matériau et les mesures des composants est plus importante lorsque le rapport du diamètre extérieur au diamètre intérieur est plus grand.

Si les pertes totales massiques doivent être déterminées, la masse de l'éprouvette d'essai doit être mesurée au moyen d'une balance étalonnée appropriée.

4.3 Enroulements

L'éprouvette d'essai doit être entourée d'un enroulement d'excitation et d'un enroulement secondaire (voir Annexe A).

Le nombre de spires dépend de l'appareillage et de la méthode de mesure employés. L'enroulement secondaire doit être enroulé aussi près que possible de l'éprouvette d'essai afin de réduire le plus possible l'effet du flux d'air se trouvant entre l'éprouvette d'essai et l'enroulement secondaire. Tous les enroulements doivent être enroulés uniformément sur toute la longueur de l'éprouvette d'essai.

Pour des mesures à des fréquences supérieures aux fréquences industrielles, des précautions doivent être prises pour éviter les complications dues aux effets de la capacité et à d'autres effets. Celles-ci sont abordées à l'Annexe A.

Des précautions doivent être prises pour que l'isolation du fil ne soit pas endommagée pendant le procédé d'enroulement, ce qui entraînerait un court-circuit dans l'éprouvette d'essai. Une vérification électrique doit être réalisée avec un appareil approprié de mesure de résistance d'isolement en courant alternatif pour s'assurer qu'il n'existe aucune connexion directe entre les enroulements et l'éprouvette d'essai.

5 Mesures de température

Lorsque la température de la surface de l'éprouvette d'essai est exigée, elle doit être mesurée en reliant un thermocouple non magnétique étalonné (un thermocouple de type T, par exemple) à l'éprouvette d'essai. Lorsque l'éprouvette d'essai est enfermée dans un boîtier annulaire, un petit trou doit être réalisé dans le boîtier en prenant soin de ne pas endommager le matériau de l'éprouvette d'essai, et le thermocouple doit être fixé au contact de l'éprouvette d'essai. Si cela n'est pas possible, le thermocouple doit être fixé au boîtier et cette procédure doit être consignée dans le rapport d'essai. Le thermocouple doit être relié à un voltmètre étalonné approprié afin de mesurer sa tension de sortie qui peut être rapportée à la température correspondante, grâce aux tables d'étalonnage du thermocouple.

Lorsque la température de l'éprouvette d'essai varie dans le temps après aimantation, les mesures des propriétés magnétiques doivent être réalisées soit lorsqu'une température convenue est atteinte, soit après un temps convenu entre les parties concernées. Si des mesures doivent être réalisées à des températures élevées, celles-ci peuvent être effectuées en plaçant l'éprouvette d'essai dans un four approprié afin d'atteindre la température exigée.

Un second effet de relaxation magnétique à constante de temps peut également modifier les propriétés magnétiques du matériau. Pour les types de matériaux couverts par le présent document, l'effet est habituellement masqué par les variations de température. Néanmoins, si de tels effets de relaxation magnétique apparaissent, il convient de maintenir l'éprouvette d'essai sous l'induction magnétique prescrite ou sous le champ magnétique prescrit pendant une période préalablement convenue avant de réaliser les mesures finales.

6 Mesure de la perméabilité d'amplitude relative et de la courbe d'aimantation en courant alternatif

6.1 Généralités

Les mesures sont réalisées en utilisant la méthode du tore aux fréquences normales entre 20 Hz et 100 kHz, la fréquence supérieure étant limitée par le fonctionnement de l'instrumentation.

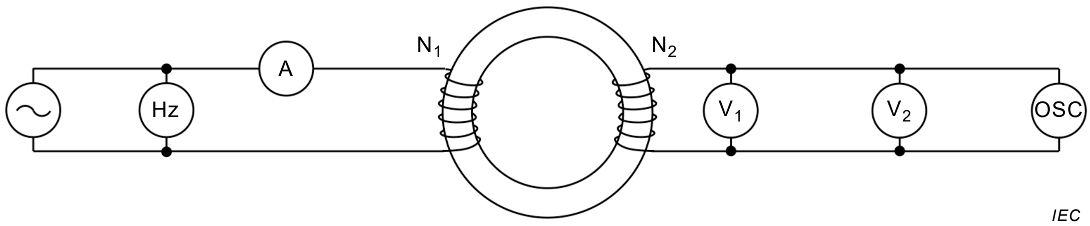
Lorsque les instruments étalonnés appropriés existent et que l'enroulement a été réalisé avec soin afin de réduire la capacité interbobinage, cette limite supérieure peut être étendue jusqu'à 1 MHz (voir Annexe A).

6.2 Appareils et branchements

Les appareils doivent être branchés conformément à la Figure 1.

NOTE 1 La Figure 3 peut être utilisée pour la mesure de la perméabilité d'amplitude relative et de la courbe d'aimantation en appliquant la technique d'échantillonnage numérique.

NOTE 2 Pour l'application de la technique d'échantillonnage numérique, voir Annexe B.



Légende

~	source de courant (habituellement un oscillateur et un amplificateur de puissance)
A	ampèremètre de valeur efficace vraie ou de valeur de crête ou voltmètre de valeur efficace vraie ou de valeur de crête, et résistance de précision non inductive pour mesurer le courant magnétisant
Hz	fréquencemètre
N_1	enroulement d'excitation
N_2	enroulement secondaire
OSC	oscilloscope
V_1	voltmètre de valeur moyenne
V_2	voltmètre de valeur efficace

Figure 1 – Circuit de l'appareillage de mesure

Lors des mesures de courant sinusoïdal, il convient de relier une résistance de précision non inductive en série à l'enroulement d'excitation N_1 afin de garantir que la résistance du circuit magnétisant soit au moins dix fois plus grande que l'impédance de l'enroulement d'excitation N_1 de l'éprouvette d'essai.

La source de courant alternatif doit présenter une variation de tension et de fréquence à sa sortie n'excédant pas pour chacune ± 0,2 % de la valeur ajustée pendant la mesure. Elle doit être reliée à un ampèremètre de valeur efficace vraie ou de valeur de crête, ou à un voltmètre de valeur efficace vraie ou de valeur de crête, et à une résistance de précision non inductive parallèle, montée en série avec l'enroulement d'excitation N_1 sur l'éprouvette d'essai, afin de mesurer le courant magnétisant.

Le circuit secondaire comporte un enroulement secondaire N_2 relié à deux voltmètres en parallèle. Un voltmètre V_2 mesure la valeur efficace vraie, tandis que l'autre voltmètre V_1 mesure la valeur moyenne redressée, mais il est parfois gradué en valeurs égales à 1,111 fois la valeur redressée.

Il convient de vérifier la forme d'onde de la tension secondaire induite dans l'enroulement secondaire N_2 au moyen d'un oscilloscope, afin de s'assurer que seule la composante fondamentale est présente.

6.3 Forme d'onde de la tension secondaire induite ou du courant magnétisant

Afin d'obtenir des mesures comparables, les mesures doivent être préalablement convenues pour que la forme d'onde de la tension secondaire induite ou la forme d'onde du courant magnétisant soit maintenue sinusoïdale avec un facteur de forme de 1,111 et une tolérance relative de ± 1 %. Dans ce dernier cas, une résistance de précision non inductive reliée en série à l'enroulement d'excitation est exigée.

NOTE 1 La forme d'onde de la tension secondaire induite et du courant magnétisant peut être mesurée en appliquant la technique d'échantillonnage numérique. Voir Figure 3 et Annexe B.

Il convient de vérifier que la constante de temps de la résistance de précision non inductive soit faible pour s'assurer que la forme d'onde se trouve dans les limites spécifiées.

La résistance de précision non inductive peut être la même résistance que celle utilisée pour la mesure du courant magnétisant.