भारतीय मानक

Indian Standard

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चुंबकीय सामग्रियाँ — सिंगल शीट टेस्टर के माध्यम से लौह-आधारित अनियतरूपी स्ट्रिप के चुम्बकीय गुण धर्मों को मापने की पद्धतियाँ

(पहला पुनरीक्षण)

Magnetic Materials — Methods of Measurement of the Magnetic Properties of Fe-Based Amorphous Strip by Means of a Single Sheet Tester

(First Revision)

ICS 17.220.20; 29.030

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NATIONAL FOREWORD

This Indian Standard (First Revision) which is identical to IEC 60404-16 : 2018 'Magnetic materials — Part 16: Methods of measurement of the magnetic properties of Fe-based amorphous strip by means of a single sheet tester' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Wrought Steel Products Sectional Committee and approval of the Metallurgical Engineering Division Council.

This standard was originally published in 2016. This revision has been undertaken to align it with the latest version of IEC 60404-8-16 : 2018 under dual numbering system to harmonize it with the latest developments that have taken place at international level.

After appropriate heat treatment, the strip exhibits quite a lower value of specific total loss in comparison to grain-oriented electrical steel strip. It is associated with low hysteresis loss due to low magnetic anisotropy and low eddy current loss due to a high resistivity and a thin thickness. However, it may deteriorate significantly by applying stress on the strip due to high magnetostriction and low magnetic anisotropy of the material. The strip is usually supplied without any insulating coating. Consequently, an effect of inter-laminar eddy-current loss may increase the specific total loss values when the strip is laminated tightly into toroidal cores. Moreover, even if construction stresses induced by bending the strip into toroidal core could be removed by heat treatments, a small change in the diameter of test specimen cases unexpected stress in the material and then deteriorated magnetic properties may be obtained.

Therefore, methods of measurement of the magnetic properties of Fe-based amorphous strip by means of a single sheet tester are required.

Several attentions are necessary for the single sheet tester. Insignificant stress applied on the material could cause deterioration of magnetic properties of the material. Effects of the flux closure yoke, an introducing on stress into the material by a weight of upper yoke could be severe for the material. Therefore, a vertical single yoke is suitable to prevent the effects caused by an upper yoke. Moreover, deformation of the test specimen near the pole faces may introduce stress into the material. The H coil method is essential to avoid detecting the deteriorated properties of the test specimen beneath the pole faces. The material has lower magnetic anisotropy due to lack of crystalline anisotropy and its permeability is quite high, so the single sheet tester is recommended to be equipped a magnetic shield to prevent unexpected magnetization by the geomagnetic field.

Thin thickness, higher permeability and low total loss of the Fe-based amorphous strip bring weak output signals from the secondary coil, the H coil and the shunt resister to measure the magnetizing current of the SST apparatus. These signals shall be amplitude using low noise pre-amplifiers before the data acquisition devices. The digital sampling method is recommended to measure these weak signals. Observations of hysteresis loops are necessary to check the quality of measurements.

The text of IEC standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions and terminologies are however not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words ‘International Standard’ appear referring to this standard, they should be read as ‘Indian Standard’; and

b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

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Indian Standard

MAGNETIC MATERIALS — METHODS OF MEASUREMENT OF THE MAGNETIC PROPERTIES OF FE-BASED AMORPHOUS STRIP BY MEANS OF A SINGLE SHEET TESTER

(First Revision)

1 Scope

This part of IEC 60404 is applicable to Fe-based amorphous strips specified in IEC 60404-8-11 for the measurement of AC magnetic properties at frequencies up to 400 Hz.

The object of this part is to define the general principles and technical details of the measurement of the magnetic properties of Fe-based amorphous strips by means of a single sheet tester.

The single sheet tester is applicable to test specimens obtained from Fe-based amorphous strips of any quality. The AC magnetic characteristics are determined for a sinusoidal induced voltage, for specified peak values of magnetic polarization and for a specified frequency.

The measurements are made at an ambient temperature of (23 ± 5) °C on test specimens which have first been demagnetized.

NOTE 1 The single sheet tester specified in this document is appropriate for other materials which have magnetic properties and physical characteristics similar to those of Fe-based amorphous strip, such as nano-crystalline soft magnetic strip. The single sheet tester for electrical steel sheets is specified in IEC 60404-3.

NOTE 2 Throughout this document the term “magnetic polarization” is used as described in IEC 60050-121. In some standards of the IEC 60404 series, the term “magnetic flux density” is used.

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 60404-8-11, *Magnetic materials – Part 8-11: Specifications for individual materials – Fe-based amorphous strip delivered in the semi-processed state*

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

4.1 Principle of the method

This document applies the wattmeter method with H coil mode for the determination of the magnetic field strength (“H coil method”). The flux closure is made by a single “U”-shaped yoke.

The test specimen comprises a Fe-based amorphous strip, which is placed inside the following two windings:

– an exterior primary winding (magnetizing winding);

– an interior secondary winding (induced voltage winding).

A H coil that detects the magnetic field strength at the surface of the test specimen is placed under the test specimen.

The flux closure is made by a single vertical “U” shaped yoke, the cross-section of which is very large compared with that of the test specimen (see Figure 1).

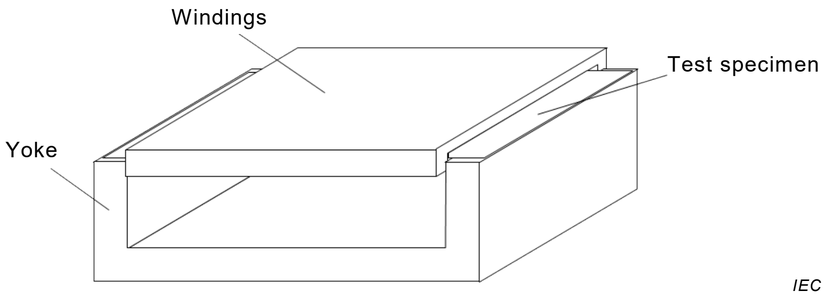
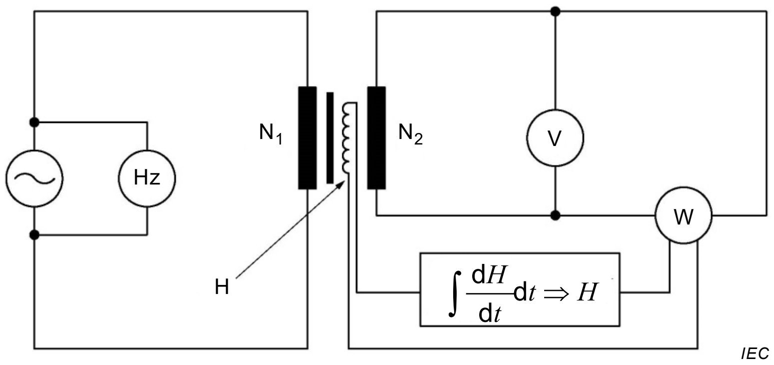


Figure 1 – Schematic diagram of the test apparatus

NOTE 1 Double yokes are unsuitable because the influence of the loading of an upper yoke on the test specimen is significant due to the large magnetostriction of the material. However, the upper yoke can be placed on the lower yoke in the absence of the test specimen to demagnetize yokes and to measure the power loss in the yokes.

The circuit diagram of Figure 2 illustrates the principle of the wattmeter method with H coil mode. The single sheet tester and the measuring instruments shall be connected as shown in Figure 2.

NOTE 2 Figure 2 also sets out the fundamentals of the widely used digital sampling technique, where the instrument functions are realised partly, or fully, through evaluating software. For the application of the digital sampling technique, see 4.6 and Annex B. Figure 2 does not show the feed-back circuit for the waveform control of the induced secondary voltage (see 4.4 and Annex C).



Key

~	power supply
Hz	frequency meter
N_1	primary winding
N_2	secondary winding
H	H coil
V	voltmeter
$\int \frac{dH}{dt} dt \Rightarrow H$	integrator
W	wattmeter

Figure 2 – Circuit of the wattmeter method with H coil mode

NOTE 3 The voltage induced in the H coil, $U_H(t)$, can be used for the air flux compensation in different ways (see 4.3.4 and Clause B.4) and for the digital sinusoidal waveform control of the induced secondary voltage, $U_2(t)$ (see 5.3 and Annex C) .

4.2 Test specimen

The test specimen shall be sampled in accordance with IEC 60404-8-11.

NOTE Nominal widths of Fe-based amorphous strip are 142,2 mm, 170,2 mm and 213,4 mm (see IEC 60404-8-11).

The length of the test specimen shall be no less than 280 mm, which is the outside dimension of the distance across the pole faces of the yoke. Although the part of the specimen situated outside the pole faces has no great influence on the measurement, this part shall not be longer than is necessary to facilitate insertion and removal of the test specimen.

The test specimen shall be cut to length from Fe-based amorphous strip without the formation of excessive burrs or mechanical distortion. The test specimen shall be plane and rectangular.

The test specimen shall be prepared by a magnetic anneal in a DC magnetic field directed parallel to the casting direction according to the instructions of the manufacturer. The test specimen shall be flat during the treatment.

Care shall be taken in handling the test specimen after the treatment in order to avoid raising fragments of the strip or creating mechanical stresses in the test specimen because the material is usually brittle after heat treatment.

4.3 Test apparatus

4.3.1 General

The test apparatus comprises the windings and the yoke (see Figure 1).

Care shall be taken to ensure that temperature changes are kept below a level likely to produce stress in the test specimen due to the distribution of thermal expansion or contraction.

4.3.2 Yoke

The yoke is in the form of a letter U built by using soft ferrite (see Figure 3). It should have a low magnetic remanence, a low reluctance and a specific total loss as low as possible.

NOTE 1 Lower quality of yoke materials can lead to poor measurement quality and to misleading results of the magnetic properties of the test specimen accordingly (see Annex A).

Dimensions in millimetres

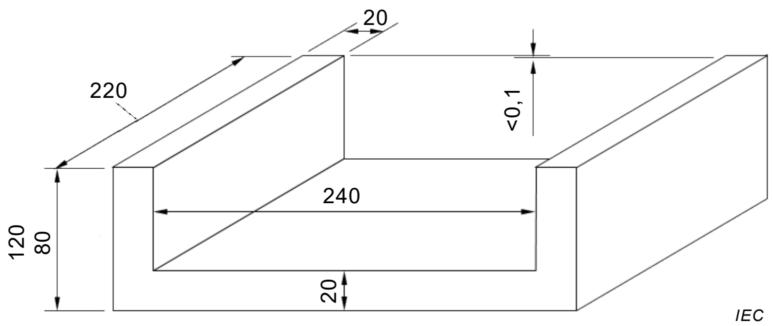


Figure 3 – Yoke dimensions

The yoke shall have pole faces having a width of 20 mm ± 1 mm.

The two pole faces of the yoke shall be as flat as possible and coplanar to within 0,1 mm. Also, the yoke shall be rigid in order to avoid creating mechanical stresses in the test specimen.

The height of the yoke shall be between 80 mm and 120 mm. The yoke shall have a width of 220 mm ± 1 mm and an inside length of 240 mm ± 1 mm (see Figure 3).

Other yoke dimensions may be used provided that comparability of the results can be demonstrated.

NOTE 2 The power loss dissipated in the yoke can be measured by making a magnetic closure circuit consisting of the yoke and a matching upper yoke that are wound with primary and secondary windings; 25 turns are sufficient for each winding.

There shall be a specimen support, which is made of non-conductive and non-magnetic materials, between the vertical limbs of the yokes. The surface of the support, on which the test specimen is supported, shall be in the same plane with the pole faces so that the test specimen can contact the pole faces with minimum air gaps.

NOTE 3 If there are steps between the surface of the test support plane and the pole faces, deteriorated magnetic properties are measured.

4.3.3 Windings

The primary winding shall be at least 230 mm in length. The secondary winding shall be 120 mm ± 1 mm in length and centred in the primary winding. The primary and secondary windings shall be wound on a non-conducting, non-magnetic and rectangular former. The dimensions of the former shall be as follows:

– length for winding: 235 mm ± 5 mm;
– internal height: 3 mm ± 1 mm;
– external height: ≤ 15 mm; the value of 12 mm is recommended.

The primary winding can be made up of a single continuous and uniform winding taking up the whole length. One example of the winding is made up of 220 turns of copper wire 1 mm in diameter taking up the whole length, wound in one or more layers.

The secondary winding shall be made up of a single continuous and uniform winding taking up the length of 120 mm ± 1 mm, wound in one layer. The number of turns on the secondary winding depends on the characteristics of the measuring instruments.

The H coil shall have the same length as the secondary winding and be centred in the primary winding. The H coil shall be wound on a non-conducting, non-magnetic and rectangular plate. The width of the plate shall be 120 mm ± 1 mm and the height of the plate shall be 3 mm ± 0,2 mm.

The H coil shall be embedded in the specimen support plate and the distance between the upper surface of the support plate and the upper surface of the H coil shall be 1 mm ± 0,2 mm.

The area-turns of the H coil shall be calibrated in a uniform field using a solenoid coil of a diameter and length large enough to obtain a uniform field over the volume of the H coil.

4.3.4 Air flux compensation

Compensation of the effect of air flux on the induced secondary voltage shall be made.

This can be achieved, for example, by the numerical air flux compensation method (see Clause B.4).

4.3.5 Magnetic shielding

A simple magnetic shielding of the single sheet tester is recommended to weaken sufficiently the effects of geomagnetic and other external magnetic fields in order to avoid unexpected magnetization of the test apparatus (see Annex A).

4.4 Power supply

The power supply should consist of a computer-controlled arbitrary signal generator and a power amplifier, or an instrument integrating both of these functions (see Figure 4).

The arbitrary signal generator shall synthesize a signal of magnetizing waveform, amplitude and frequency data, which are programmed externally. A low pass filter should be inserted between the arbitrary signal generator and the power amplifier to prevent aliasing at the measuring instruments.

The frequency shall be measured with an accuracy of ±0,1 % or better.

The waveform of the induced secondary voltage shall be maintained as sinusoidal as possible. It is preferable not only to maintain the form factor of the induced secondary voltage to within 1,111 with a relative tolerance of ±1 %, but also to suppress harmonic contents in the induced secondary voltage to as low as possible. This can be achieved by various means, using analogue feedback control or by digital means described in Annex C.

The power amplifier shall be of low internal impedance and shall be highly stable in terms of voltage and frequency, being with sufficiently low voltage noise. During the measurement, the voltage and frequency shall be maintained constant within ±0,2 %.

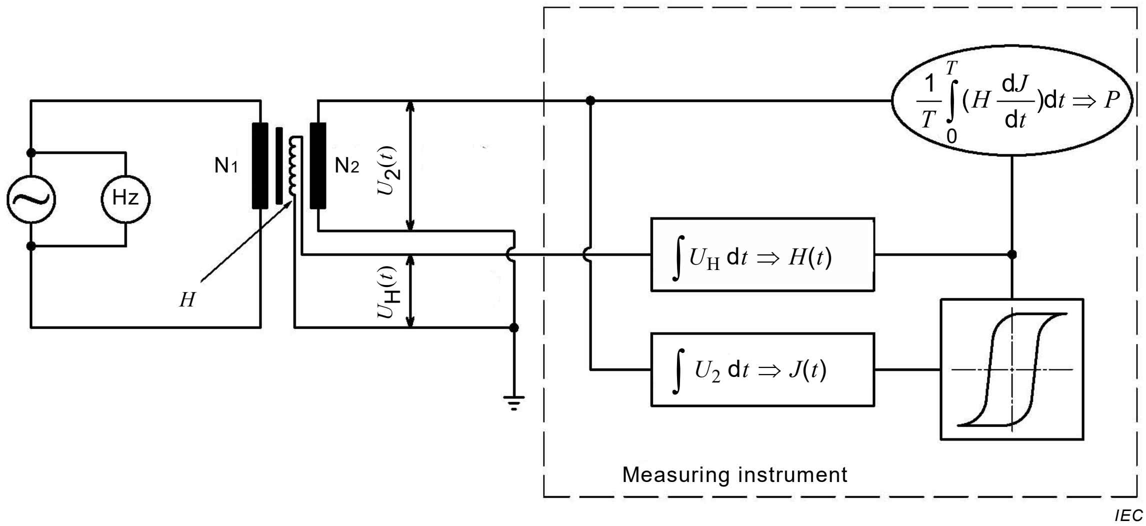
The power amplifier should be a bipolar type with low noise and wide ranges of frequency and voltage.

4.5 Measuring instruments

The measuring instruments shall meet the following specifications: The power shall be measured with an accuracy of ±0,5 % or better at the actual power factor and crest factor. The voltages shall be measured with an accuracy of ±0,5 % or better.

4.6 Digital sampling technique

The fundamental circuit of the digital sampling technique, almost exclusively used for this kind of measurement, is shown in Figure 4, in this case employing the H coil combined with the integrator for the determination of the magnetic field strength (for technical details see also Annex B). The measuring instrument is usually composed of preamplifiers, a digitizer and a digital signal calculator, and provides the functions of the wattmeter and voltmeter shown in Figure 2 in the software.



Key

~	power supply
Hz	frequency meter
N_1	primary winding
N_2	secondary winding
H	H coil
$U_2(t)$	voltage induced in the secondary winding
$U_H(t)$	voltage induced in the H coil
$\int U_H dt \Rightarrow H(t)$	H-integrator function of software
$\int U_2 dt \Rightarrow J(t)$	J-integrator function of software
$\frac{1}{T}\int_0^T (H\frac{dJ}{dt})dt \Rightarrow P$	wattmeter and voltmeter functions of software

Figure 4 – Circuit of the wattmeter method with H coil mode adopting the digital sampling technique

NOTE 1 The numerical air flux compensation, $J = B - \mu_0 \times H$, is not presented in Figure 4 but is included in the software, see 4.3.4. Figure 4 does also not show the possible analogue feed-back circuit for the waveform control of the induced secondary voltage (see 4.4). The waveform control can also be managed by digital means (see the paragraph before the last one in 4.6 and Annex C).

The following signals shall be measured:

– the voltage induced in the secondary winding, $U_2(t)$;
– the voltage induced in the H coil, $U_H(t)$;

The data set of signals $U_H(t)$ and $U_2(t)$ sampled over one period of magnetization provides the complete information for one measurement.

The magnetic field strength $H(t)$, the magnetic polarization $J(t)$, the specific total loss P_s and the specific apparent power S_s shall be calculated from $U_H(t)$ and $U_2(t)$ by the function of the field measuring devices and the wattmeter in the measuring instrument, see Clause 6.

The measuring instrument using the digital sampling technique is comprised of calibrated preamplifiers for each signal channel, a calibrated digitizer and a digital signal calculator. The measuring instrument has two independent signal channels corresponding to $U_2(t)$ and $U_H(t)$ working simultaneously with a sampling clock that is synchronized with the readout clock of the arbitrary signal generator. Unsynchronized sampling is also used; however, a higher sampling rate is then required to achieve the same accuracy (see Annex B).

The signal channels shall have sufficiently high input impedance (typically > 1 MΩ in parallel with about 100 pF) to avoid the load on the secondary winding. The phase shift difference between the channels shall be sufficiently small even at the lowest power factor.

The digital signal calculator calculates the magnetic properties through the evaluating software.

The digital signal calculator may create the digital feedback signal to feed into the arbitrary signal generator for the sinusoidal waveform control of the magnetic polarization by digital means (see Annex C).

The instrument specifications established in 4.5 shall also be applied to the digital sampling technique.

NOTE 2 For the technical details and requirements of the digital sampling technique, see Annex B.

5 Measurement procedure

5.1 Principle of measurement

The apparatus and the windings shall be connected as shown in Figure 2 or Figure 4, as applicable.

If the digital sampling technique is employed, the voltage induced in the secondary winding $U_2(t)$ and the voltage induced in the H coil $U_H(t)$ shall be measured as time functional signals.

The magnetic field strength $H(t)$, the magnetic polarization $J(t)$, the specific total loss P_s and the specific apparent power S_s shall be calculated from $U_H(t)$ and $U_2(t)$.

NOTE For the technical details and requirements of the digital sampling technique, see Annex B.

5.2 Preparation of measurement

The length of the test specimen and its mass shall be measured with an accuracy of ±0,1 %. The test specimen shall be loaded and centred on the longitudinal and transverse axes of the windings.

The cross-sectional area of the test specimen shall be calculated from Formula (1).

$$A = \frac{m}{l\rho_{\mathrm{m}}} \tag{1}$$

where

A	is the cross-sectional area of the test specimen, in square metres;
m	is the mass of the test specimen, in kilograms;
l	is the length of the test specimen, in metres;
ρ_{m}	is the density of the test material, in kilograms per cubic metre.

Prior to measurement, the test specimen shall be carefully demagnetized from well above the value of magnetic field strength to be measured, by slowly reducing the corresponding magnitude of the alternating magnetizing current to zero.

5.3 Adjustment of power supply

In practice, single or grouped peak values of magnetic polarization $\hat{J}$ and magnetic field strength $\hat{H}$ are set at a specified frequency.

For the measurements of the specific total loss P_{s}, the specific apparent power S_{s}, r.m.s. value of magnetic field strength $\tilde{H}$ and the peak value of the magnetic field strength $\hat{H}$, the peak value of magnetic polarization $\hat{J}$ shall be set by adjusting the power supply.

For the measurement of the peak value of magnetic polarization $\hat{J}$, the peak value of magnetic field strength $\hat{H}$ shall be set.

The values of $\hat{H}$ and $\hat{J}$ shall be calculated from $U_{\mathrm{H}}(t)$ and $U_2(t)$ measured over one or several periods of magnetization respectively, using formulas corresponding to Formulas (2) and (3), respectively.

The output of the power supply shall be slowly increased until $\hat{J}$ or $\hat{H}$ has reached the desired value. The output of the power supply shall not decrease during the measurement.

The waveform of the induced secondary voltage $U_2(t)$ should be checked to ensure that only the fundamental component is present. In addition, the shape of the hysteresis loop composed of $H(t)$ and $J(t)$ should be checked to ensure that a symmetrical loop is presented.

6 Determination of characteristics

6.1 Determination of the magnetic polarization

The magnetic polarization $J(t)$ shall be calculated from Formula (2).

$$J(t) = \frac{1}{N_2 A}\left\{\int_0^t U_2(\tau)\mathrm{d}\,\tau - \frac{1}{T}\int_0^T\left(\int_0^t U_2(\tau)\mathrm{d}\,\tau\right)\mathrm{d}\,t\right\} \tag{2}$$

where

$J(t)$	is the magnetic polarization, in teslas;
N_2	is the number of turns of the secondary winding;
A	is the cross-sectional area of the test specimen, in square metres;
$U_2(t)$	is the induced secondary voltage, in volts;
τ	is an auxiliary time variable.

The second term in the brackets of Formula (2) is the time average over the length of a period which compensates for the integration constant.

6.2 Determination of the magnetic field strength

The magnetic field strength $H(t)$ shall be calculated from Formula (3).

$$H(t) = \frac{1}{\mu_0 \left(N_H A_H\right)} \left\{ \int_0^t U_H(\tau) \mathrm{d}\tau - \frac{1}{T} \int_0^T \left(\int_0^t U_H(\tau) \mathrm{d}\tau \right) \mathrm{d}t \right\} \quad (3)$$

where

$H(t)$	is the magnetic field strength, in amperes per metre;
μ_0	is the magnetic constant ($4\,\pi \times 10^{-7}$ henrys per metre);
$(N_H A_H)$	is the area-turns of the H coil, in square metres;
$U_H(t)$	is the voltage induced in the H coil, in volts;
τ	is an auxiliary time variable.

The second term in the brackets of Formula (3) is the time average over the length of a period which compensates for the integration constant.

NOTE For the determination of the area-turns of H coil, see 4.3.3.

6.3 Determination of the specific total loss

The specific total loss P_s, corresponds to the area of the hysteresis loop formed by the magnetic field strength $H(t)$ and the magnetic polarization $J(t)$, and shall be calculated from Formula (4).

$$P_s = \frac{f}{\rho_m} \int_{t=0}^{T} H(t) \frac{\mathrm{d}J(t)}{\mathrm{d}t} dt = \frac{f}{\rho_m N_2 A} \int_{t=0}^{T} H(t) U_{2c}(t) \mathrm{d}t \quad (4)$$

where

P_s	is the specific total loss of the test specimen, in watts per kilogram;
ρ_m	is the conventional density of the test material, in kilograms per cubic metre;
f	is the frequency of the magnetization, in hertz;
T	is the magnetizing period where $T = 1/f$, in seconds;
N_2	is the number of turns of the secondary winding;
A	is the cross-sectional area of the test specimen, in square metres;
$H(t)$	is the magnetic field strength, in amperes per metre;
$J(t)$	is the magnetic polarization, in teslas;
$U_{2c}(t)$	is the air flux compensated induced secondary voltage, in volts.

NOTE 1 For the air flux compensation, $J = B - \mu_0 \times H$, see 4.3.4.

NOTE 2 In the first integral of Formula (4), $\int_{t=0}^{T} H(t) \frac{\mathrm{d}J(t)}{\mathrm{d}t} dt$, B was replaced by J because the contribution of the air flux, the integral $\int_{t=0}^{T} H(t) \frac{\mu_0 \mathrm{d}H(t)}{\mathrm{d}t} dt$, is zero.

6.4 Determination of the specific apparent power

The specific apparent power S_s shall be calculated from Formula (5).

$$S_s = 2\pi f \frac{1}{\rho_m} \tilde{H} \cdot \tilde{J} \tag{5}$$

where

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

f is the frequency of the magnetization, in hertz;

ρ_m is the conventional density of the test material, in kilograms per cubic metres;

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

$\tilde{J}$ is the r.m.s. value of magnetic polarization $J(t)$, in teslas.

7 Reproducibility

The reproducibility of this method using the test apparatus defined above is characterized by a relative standard deviation of 3 % or less for the specific total loss at 1,3 T and 1,4 T, about 1 % for the peak value of magnetic polarization at 80 A/m, and about 6 % for the specific apparent power at 1,3 T and 1,4 T.

Annex A
(informative)

Requirements of the single sheet tester for Fe-based amorphous strip

A.1 Shape of test specimen

The test specimen should be kept flat in the test apparatus. The magnetic properties of Fe-based amorphous strip can be deteriorated significantly with a small deformation of its shape because of the high magnetoelastic sensitivity of the material.

The test method using a toroidal test specimen in accordance with IEC 60404-6 [2] is unsuitable because a small change in diameter of the test specimen is usually unavoidable and then deteriorated magnetic properties may be obtained.

A.2 H coil method

The wattmeter method with the determination of the magnetic field strength from the magnetizing current ("MC method"), measures magnetic properties including the effects of the yoke. Thus, this combination is unsuitable for thin and low loss materials such as Fe-based amorphous strip. In contrast, the wattmeter method with H coil mode ("H coil method"), measures only the magnetic properties of test specimen at the area apart from the pole faces of yoke. Therefore, the loss values measured using the MC method are usually indicated higher than the values when the H coil method is used.

To apply the H coil method, a key point is to connect one terminal of the signal from the H coil and one terminal of the signal from the secondary winding as shown in Figure 4. It results in an effective reduction of high frequency noise on the signal of the H coil. Larger area-turns of the H coil and amplification of the H coil signal by a high quality preamplifier with low noise and low phase shift are also key points. A preamplifier powered by a clean DC power source is preferential in order to be free from power frequency noise.

Synchronous averaging of the signals over several periods is effective to remove noise on the signals except the noise of power frequency when the frequency of the magnetization is the same as the power frequency.

A.3 Yoke

The yoke material has low magnetic remanence and low values of specific total loss at low magnetization to reduce DC bias of magnetization of the test specimen. Soft ferrite is suitable for the yoke material.

A single yoke is more suitable than double yokes. The magnetic properties of Fe-based amorphous strip are very sensitive to stress. The upper yoke will apply stress in the parts of the test specimen near the pole faces of the yokes, and, as a result, the magnetic properties become deteriorated. Moreover, the large magnetostriction of Fe-based amorphous material causes compressive stress in the material if both ends of the test specimen are clamped between the pole faces of the yokes. These effects are considered larger than loss increases by planar eddy currents in the very thin test specimen caused by the asymmetric transition of the flux in the single yoke.

A.4 Wirings

The voltage induced in the H coil $U_H(t)$ is low and can easily be superimposed by high frequency noise. To reduce the noise on the output signal, the wires between windings and the measuring instrument should be connected as shown in Figure 4; each pair of terminals is connected on one side with the common ground.

A.5 Non-inductive precision resistor

A non-inductive precision resistor having an accuracy of ±0,1 % or better is used to measure the magnetizing current that is used for the sinusoidal waveform control of the magnetic polarization by digital means (see Annex C). The resistance value is 1 Ω or less in order to minimize the distortion of the magnetic polarization signal.

A four-terminal resistor of sufficient heat capacity should be used. The two current terminals are connected in series with the primary winding and the two potential terminals are connected to a signal channel of the measuring instrument.

A.6 Magnetic shielding

Since the magnetic permeability of Fe-based amorphous strip is very high, it is preferable that the single sheet tester is equipped with a magnetic shield. Even if the magnetic axis of the test apparatus is oriented at right angles to the direction of the earth's magnetic field , the geomagnetic field can magnetize the test specimen, to a substantial degree, in the transverse direction to the magnetic axis. A simple magnetic shield can avoid this unexpected magnetization of the test specimen by the external magnetic field.

A.7 Method for checking the stability of the installed H coil from time to time

After the H coil is installed in the former, the area-turns of the H coil may be checked in comparison of the peak values of magnetic field strength obtained by the H coil and a reference H coil of known area-turns placed in the centre of the windings without the test specimen. The reference H coil can be previously calibrated in an uniform field.

A simple alternative method without a reference coil is to feed a stable and known exciting current through the primary winding in the absence of the test specimen in the test apparatus and comparing the H coil output with the value recorded earlier, kept as a reference value. Besides the simplicity, the advantage of the simple method is avoiding error introduced by the positioning of the reference coil.

NOTE The calibration of the area-turns of the H coil in a uniform field using a solenoid coil of a diameter and length large enough to obtain a uniform field over the volume of the H coil is described in 4.3.3.

Annex B
(informative)

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

B.1 General

The digital sampling technique is an advanced method that is almost exclusively applied to the electrical part of the measurement procedure of this document [3-5]. Applied to the wattmeter method with H coil mode, it is characterized by the digitization of the voltage $U_2(t)$ induced in the secondary winding and the voltage $U_H(t)$ induced in the H coil, and by the evaluation of these data for the determination of the magnetic properties of the test specimen.

For this purpose, instantaneous values of these voltages having index j, u_{2j} and u_{Hj} 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.

Figure 4 represents the circuit of the wattmeter method with H coil mode adopting the digital sampling technique based on the principle of the circuit shown in Figure 2. The digital sampling technique allows all functions of the measurement equipment in Figure 2 to be realised 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 realised by a digital means as is shown in Annex C.

Annex B is helpful in understanding the impact of the digital sampling technique on the precision 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 [6-8].

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 $\mathrm{d}t$ by the finite time interval Δt:

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

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 [7]) and the sampling frequency, f_s, should be greater than twice the input signal bandwidth.

The windings of the test apparatus are connected as shown in Figure 4.

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 measuring instruments. The measuring instrument usually consists of preamplifiers for each signal channel, a calibrated digitizer and a digital signal calculator (usually a personal computer).The preamplifier should have a high input impedance (typically >1 MΩ in parallel with 90 pF to 150 pF) to avoid loading the secondary circuit and amplifies the input signal into voltage suitable for digitizing with high signal-to-noise ratio. It is recommended that the sampling clock of the digitizer should be synchronized with the clock of the digital signal generator (Nyquist condition).

The measuring instrument digitizes the voltage induced in the secondary winding and the voltage induced in the H coil simultaneously into instantaneous values u_{m2j} and u_{mHj}, respectively. The values u_{m2j} and u_{mHj} should be corrected by the factor, $\frac{R_i + R_2}{R_i}$ and $\frac{R_i + R_H}{R_i}$, respectively, to compensate for the voltage drop through the resistances of the instruments in the measuring circuit. Therefore, the values are calculated as follows:

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

$$u_{Hj} = \frac{R_i + R_H}{R_i} u_{mHj} \quad \text{(B.3)}$$

where

- u_{m2j} is the measured instantaneous value of the voltage induced in the secondary winding, in volts;
- u_{mHj} is the measured instantaneous value of the voltage of the H coil, in volts;
- u_{2j} is the instantaneous value of the voltage induced in the secondary winding, in volts;
- u_{Hj} is the instantaneous value of the voltage induced in the H coil, in volts;
- R_i is the input resistance of the measuring instrument, in ohms;
- R_2 is the resistance of the secondary winding, in ohms;
- R_H is the resistance of the H coil, in ohms.

Instantaneous values of the magnetic field strength h_j are calculated as follows:

$$h_j = h'_j - \frac{1}{n}\sum_{k=0}^{n-1} h'_k \quad \text{(B.4)}$$

The second term of Formula (B.4) is the average over the length of a period which compensates for the integration constant. The signal h'_j is the result of the integration of the digitalized voltage measured at the H-coil which includes the integration constant and is to be calculated as follows:

$$h'_j = \frac{1}{\mu_0 f_s (N_H A_H)} \sum_{k=0}^{j} u_{Hk} \quad \text{(B.4A)}$$

The digital signal calculator reconstructs the data arrays of h_j, u_{2j} and u_{Hj} into numerical signals of voltages $H(t)$,$U_2(t)$ and $U_H(t)$ 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 polarization *J(t)* can be calculated by using

$$J(t) = \frac{1}{N_2 A}\left\{\int_0^t U_2(\tau)\mathrm{d}\,\tau - \frac{1}{T}\int_0^T\left(\int_0^t U_2(\tau)\mathrm{d}\,\tau\right)\mathrm{d}\,t\right\} \tag{B.5}$$

τ is an auxiliary time variable.

The second term in the brackets of Formula (B.5) is the time average over the length of a period which compensates for the integration constant.

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:

$$\hat{J} = \frac{1}{4fN_2A}\frac{1}{T}\int_{t=0}^{T}\left|U_2(t)\right|dt \cong \frac{1}{4f_\mathrm{s}N_2A}\sum_{j=0}^{n-1}\left|u_{2j}\right| \tag{B.6}$$

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

$$P_\mathrm{s} = \frac{1}{\rho_\mathrm{m}T}\int_{\mathrm{t}=0}^{T}H(t)\frac{\mathrm{d}J(t)}{\mathrm{d}t}\mathrm{d}t \cong \frac{1}{N_2A\rho_\mathrm{m}}\frac{1}{n}\sum_{j=0}^{n-1}h_j u_{2j} \tag{B.7}$$

and the calculation of the specific apparent power follows:

$$S_\mathrm{s} = \frac{1}{N_2A\rho_\mathrm{m}}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}{h_j}^2}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}{u_{2j}}^2} \tag{B.8}$$

where

$J(t)$ is the magnetic polarization, in function of time, in teslas;

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

$\hat{J}$ is the peak value of the magnetic polarization, 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 frequency of the magnetization, in hertz;

f_s is the sampling frequency, in points per second;

N_2 is the number of turns of the secondary winding;

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

$(N_\mathrm{H}A_\mathrm{H})$ is the area-turns of the H coil, in square metres;

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

ρ_m is the conventional density of the test material, in kilograms per cubic metre;

h_j is the instantaneous value of the magnetic field strength, in amperes per metre;

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, k are the indexes of instantaneous values;

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

$U_H(t)$ is the voltage induced in the H coil, in function of time, in volts.

NOTE With the H coil method, a correction term of the power consumed by the instruments in the secondary circuit loss is not necessary for the calculation of the specific total loss.

The pairs of values, u_{Hj} and u_{2j}, can then be processed by a computer or, for real time processing, by 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, $U_H(t)$ and $U_2(t)$ may be scanned using 128 samples per period with sufficient accuracy. 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 [9] 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 [7] is recommended in order to eliminate irrelevant higher frequency components which would otherwise interact with the digital sampling process producing aliasing noise.

Regarding the amplitude resolution, studies [6, 9] have shown that below a 12-bit resolution, the digitization error can be considerable, particularly for non-oriented material with high silicon content. 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. 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) and the higher the frequency is. 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 standard makes careful calibration of the measurement equipment necessary. The two voltage channels including preamplifiers and ADCs can be calibrated using a calibrated reference AC voltage source traceable to national standards [8]. 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 digital signal calculator. In any case, it would not be sufficient to calibrate the set-up using reference samples because the Fe-based amorphous strip is quite sensitive to stress that could be applied on the sample during repetition of measurements.

B.4 Numerical air flux compensation

The numerical air flux compensation method is similar to the principle of mutual inductor.

Applied to the H coil method, the compensation can be carried out as follows:

$$U_{2c}(t) = U_{2m}(t) - \mathrm{C} \cdot U_{H}(t) \quad \text{(B.9)}$$

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;

$U_{H}(t)$ is the voltage induced in the H coil, in volts.

The adjustment of the value of compensation factor C can be made so that, when passing an alternating current through the primary winding in the absence of the test specimen in the test apparatus, the compensated voltage must be no more than 0,1 % of the non-compensated voltage appearing across the secondary winding alone, corresponding to the condition of maximum magnetic flux density such as 80 A/m.

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

Annex C
(informative)

Sinusoidal waveform control of the magnetic polarization by digital means

The prescribed sinusoidal waveform of the magnetic polarization may be difficult to achieve by means of conventional analogue feedback techniques. Instabilities and auto-oscillations are likely to occur when the magnetic polarization is increased beyond the knee of the magnetization curve. The digital means is expected to be immune from auto-oscillatory effects.

The voltage $U_g(t)$ to be fed into the arbitrary signal generator can be calculated from Formula (C.1) neglecting spurious capacitance effects [4,5,10,11].

$$U_g(t) = \frac{1}{G}\left(N_1\left(A\frac{dJ(t)}{dt} + \mu_0 A_1 \frac{dH(t)}{dt}\right) + R_S I(t)\right) = \frac{1}{G}\left(AN_1\frac{dJ(t)}{dt} + \frac{\mu_0 A_1 N_1^2}{l_m}\frac{dI(t)}{dt} + R_S I(t)\right) \quad \text{(C.1)}$$

where

$U_g(t)$	is the voltage to be fed into the arbitrary signal generator, in volts;
G	is the gain of the power amplifier;
N_1	is the total number of turns of the primary winding;
N_2	is the total number of turns of the secondary winding;
$J(t)$	is the target magnetic polarization, in teslas;
$H(t)$	is the magnetic field strength, in amperes per metre;
$I(t)$	is the magnetizing current, in amperes;
A	is the cross-sectional area of the test specimen, in square metres;
A_1	is the effective cross-sectional area of the primary winding, in square metres;
l_m	is the conventional effective magnetic path length, in metres (l_m = 0,24 m);
μ_0	is the magnetic constant; $4\pi \times 10^{-7}$ henrys per metre;
R_s	is the total series resistance of the magnetizing circuit, in ohms.

An iterative method of signal waveform control is possible. A voltage $U_{i+1}(t)$, to be fed into the computer controlled arbitrary signal generator at $(i+1)$-th step, can be calculated from Formula (C.2). The voltage $U_{i+1}(t)$ is calculated from the difference between the measured voltages induced in the second winding $U_2(t)$ and the target voltage induced in the second winding for the desired set point $U_J(t)$. The iteration can be stopped once the prescribed form factor value 1,111 with a relative tolerance of ±1 % of the magnetic polarization is attained.

$$U_{i+1}(t) = U_i(t) + \mathrm{K}\frac{N_1}{GN_2}\left(U_J(t) - U_2(t)\right) \quad \text{(C.2)}$$

where

$U_{i+1}(t)$	is the voltage to be fed into the arbitrary signal generator at $(i+1)$-th step, in volts;
K	is the constant of negative-feedback; positive value below 1,0;
G	is the gain of the power amplifier;
$U_J(t)$	is the calculated voltage induced in the secondary winding when the set magnetic polarization has been achieved, in volts;
$U_2(t)$	is the voltage induced in the secondary winding, in volts.

Because the signal control by digital means is the repetition of magnetization, acquisition of the signals, demagnetization and signal control, the total time for signal control becomes longer compared with the analogue case. In order to reduce the total control time, a special apparatus that switch the signals $U_i(t)$ to $U_{i+1}(t)$ seamlessly can be adopted to omit the demagnetization.

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[2] A consolidated version of this publication exists, comprising IEC 60404-3:1992, IEC 60404-3:1992/AMD1:2002 and IEC 60404-3:1992/AMD2:2009.

(*Continued from second cover*)

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards which are to be substituted in their place are listed below along with their degree of equivalence for the edition indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60404-8-11 : 2018 Magnetic materials — Part 8-11: Specifications for individual materials — Fe-based amorphous strip delivered in the semi-processed state	IS 16585 : 2023 Magnetic materials — Specifications for individual materials — Fe-based amorphous strip delivered in the semi-processed state (IEC 60604-8-11 : 2018, MOD) (*first revision*)	Modified

The Committee responsible for the preparation of this standard has reviewed the provisions of following International Standards referred in these adopted standards and has decided their acceptability for use in conjunction with this standard:

International Standard	*Title*
IEC 60050-121 : 1998	International electrotechnical vocabulary (IEV) — Part 121: Electromagnetism
IEC 60050-221 : 1990	International electrotechnical vocabulary (IEV) — Part 221: Magnetic materials and components

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 2022 'Rules for rounding off numerical values (*second revision*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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Amendments Issued Since Publication

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