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Magnetic materials –
Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester

IEC 60404-3:2022-11 RLV(en)

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MAGNETIC MATERIALS –

Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester

FOREWORD

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IEC 60404-3 has been prepared by IEC technical committee 68: Magnetic alloys and steels. It is an International Standard.

This third edition cancels and replaces the second edition published in 1992, Amendment 1:2002 and Amendment 2:2009. This edition constitutes a technical revision.

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

a) Annex A was revised. The method of determining the yokes' lamination resistance was added to Annex A;
b) Annex B of the consolidated version of 2010 referred to calibration of the SST using the Epstein method. It was cancelled;
c) Annex B (new), Annex C and Annex D were revised, they are for information only;
d) Annex C was modified taking account of the new situation regarding P and R grades;
e) Annex D was amended by addition of Clause D.4 on the numerical air flux compensation.

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

Draft	Report on voting
68/699/CDV	68/710/RVC

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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 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- withdrawn,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
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MAGNETIC MATERIALS –

Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester

1 ~~Object and field of application~~ Scope

This part of IEC 60404 is applicable to grain-oriented and non-oriented electrical steel strip and sheet for measurement of AC magnetic properties at power frequencies.

The object of this document is to define the general principles and the technical details of the measurement of the magnetic properties of ~~magnetic sheets~~ electrical steel strip and sheet by means of a single sheet tester (SST).

~~This part of IEC 60404 is applicable at power frequencies to:~~

~~a) grain oriented magnetic sheet and strip:~~

~~for the measurement between 1,0 T and 1,8 T of:~~

~~– specific total loss;~~

~~– specific apparent power;~~

~~– r.m.s. value of the magnetic field strength;~~

~~for the measurement up to peak values of magnetic field strength of 1 000 A/m of:~~

~~– peak value of the magnetic polarization;~~

~~– peak value of the magnetic field strength.~~

~~b) non-oriented magnetic sheet and strip:~~

~~for the measurement between 0,8 T and 1,5 T of:~~

~~– specific total loss;~~

~~– specific apparent power;~~

~~– r.m.s. value of excitation current;~~

~~for the measurement up to peak values of magnetic field strength of 10 000 A/m of:~~

~~– peak value of the magnetic polarization;~~

~~– peak value of the magnetic field strength.~~

The single sheet tester is applicable to test specimens obtained from ~~magnetic sheets and strips of any quality~~ electrical steel strips and sheets of any grade. The AC magnetic characteristics are determined for sinusoidal induced voltages, for specified peak values of the magnetic polarization, for specific peak values of the magnetic field strength 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 Throughout this document, the quantity "magnetic polarization" is used as defined in ~~IEC 60050(901)~~ IEC 60050-221. In some standards of the IEC 60404 series, the quantity "magnetic flux density" was used.

In order to support the long-term reliability of the performance of this set up and to understand better the relationship between the Epstein method and the SST method, the informative Annexes B and C, respectively, have been included.

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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 – Part 221: Magnetic materials and components*

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

IEC 60404-13, *Magnetic materials – Part 13: Methods of measurement of resistivity, density and stacking factor of electrical steel strip and sheet*

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 https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

4 General principles of AC measurements

4.1 General

Clause 4 specifies the general conditions for the determination of AC magnetic properties of electrical steel strip and sheet at power frequencies by means of a single sheet tester.

4.2 Principle of the single sheet tester method

The test specimen comprises a sample of ~~magnetic~~ electrical steel sheet and is placed ~~inside~~ in the center of two concentric windings:

– an exterior primary winding (magnetizing winding);
– an interior secondary winding (voltage winding).

The flux closure is made by a magnetic circuit consisting of two identical yokes, the cross-section of which is very large compared with that of the test specimen (see Figure 1).

~~To minimize the effects of pressure on the test specimen, the upper yoke shall be provided with a means of suspension which allows part of its weight to be counterbalanced in accordance with 3.2.1.~~

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

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4.3 Test apparatus

4.3.1 Yokes

Each yoke is in the form of a U made up of insulated sheets of grain-oriented ~~silicon~~ electrical steel ~~or nickel iron alloy~~. It shall have a low reluctance and a low specific total loss ~~not greater than 1,0 W/kg at 1,5 T and 50 Hz~~ in the low magnetic polarization region below 0,2 T (see Annex A). It shall be manufactured in accordance with the requirements of Annex A.

In order to reduce the effect of eddy currents and give a more homogeneous distribution of the flux over the inside of the yokes, the ~~latter~~ yokes shall be made of a pair of wound cut C-cores or a glued stack of laminations in which case the corners shall have staggered butt joints (see Figure 1).

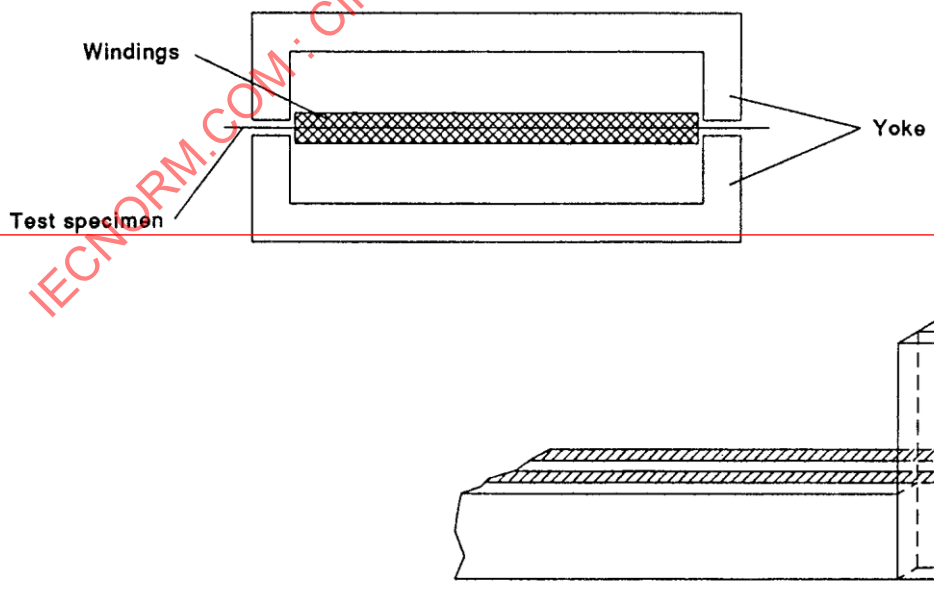
The yoke shall have pole faces having a width of 25 mm ± 1 mm.

The two pole faces of each yoke shall be coplanar to within 0,5 mm and the gap between the opposite pole faces of the yokes shall not exceed 0,005 mm at any point. Also, the yokes shall be rigid in order to avoid creating mechanical stresses such as twisting, tensioning and compression in the test specimen.

The height of each yoke shall be between 90 mm and 150 mm. Each yoke shall have a width of 500^{+5}_{-0} mm and an inside length of 450 mm ± 1 mm (see Figure 2).

~~NOTE It is recognized that other yoke dimensions can be used provided that the comparability of the results can be demonstrated.~~

There shall be a non-conducting, non-magnetic support on which the test specimen is placed, between the vertical limbs of the bottom yokes. This support shall be centered and located in the same plane as the bottom yoke pole faces so that the test specimen is in direct contact with the pole faces without any gap. Care shall be taken that in no case the upper surface of the support is positioned higher than the plane of the pole faces of the bottom yoke.



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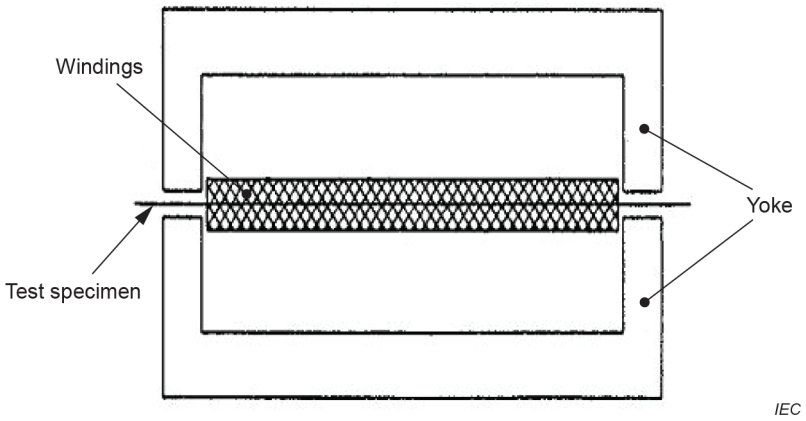
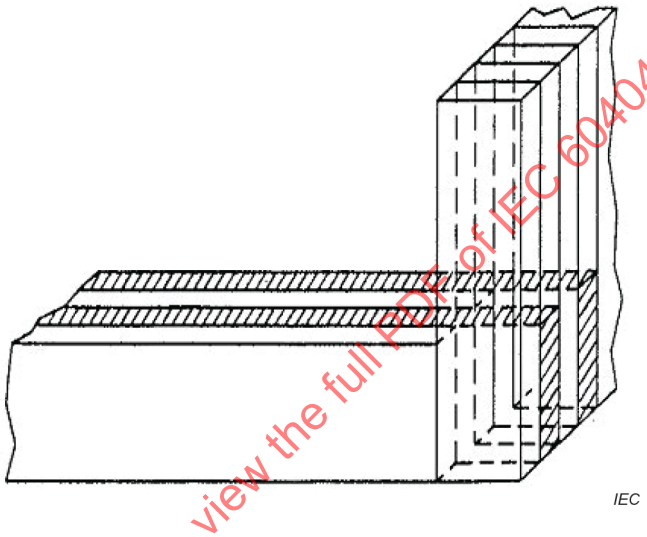


a) Cross-section of the SST



b) Schematic view of the corner of a yoke with stacked lamination

Figure 1 – Schematic diagrammes of the test apparatus

The upper yoke shall be movable upwards to permit insertion of the test specimen. ~~After insertion the upper yoke shall be realigned accurately with the bottom yoke.~~ After insertion of the test specimen, the upper yoke shall be lowered to close the magnetic circuit and, simultaneously, the pole faces of the bottom and upper yokes shall be aligned accurately. To minimize the effects of pressure on the test specimen, the upper yoke shall be provided with a means of suspension. The suspension of the upper yoke shall allow part of its weight to be counterbalanced so as to give a force on the test specimen of between 100 N and 200 N.

NOTE The square ~~shape~~ configuration of the yoke has been chosen in order to have only one test specimen for non-oriented material. By rotating the test specimen through 90°, it is possible to determine the characteristics in the rolling direction and perpendicular to the rolling direction.

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Dimensions in millimetres

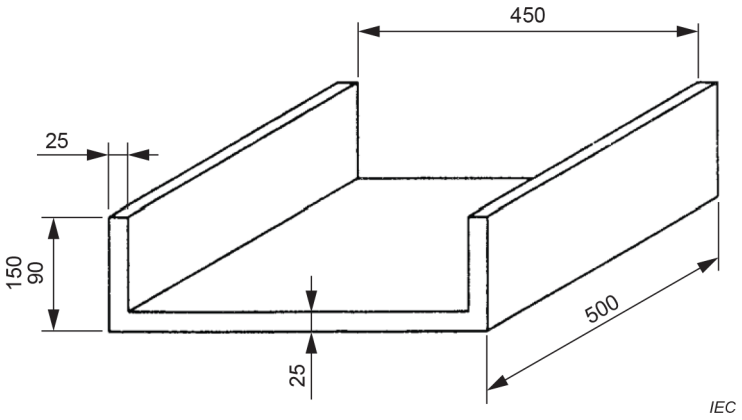

Figure 2 – Yoke dimensions

4.3.2 Windings

The coil system inside the yokes shall have two windings:

– a primary winding, on the outside (magnetizing winding);
– a secondary winding, on the inside (voltage winding);

The primary (outer) and secondary (inner) windings shall be at least 440 mm in length and shall be wound uniformly on a non-conducting, non-magnetic and rectangular former. The dimensions of the former shall be as follows:

– length: 445 mm ± 2 mm;
– internal width: 510 mm ± 1 mm;
– internal height: 5^{0}_{-2} mm;
– height: ≤ 15 mm.

The primary winding can be made up of:

– either five or more coils having identical dimensions and the same number of turns connected in parallel and taking up the whole length (see Figure 3). For example, with five coils, each coil can be made up of 400 turns of copper wire 1 mm in diameter, wound in five layers;
– or a single continuous and uniform winding taking up the whole length. For example, this winding can be made up of 400 turns of copper wire 1 mm in diameter, wound in one ~~or more layers~~ layer.

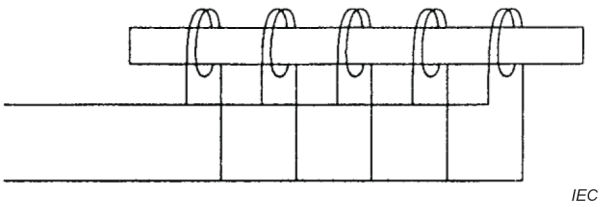

Figure 3 – Diagram of the connections of the five coils of the primary winding

The number of turns on the secondary winding will depend on the characteristics of the measuring instruments. In any case, the determination of the number of turns of the primary and secondary windings shall be made with greatest reliability because a mistake would mean a permanent error.

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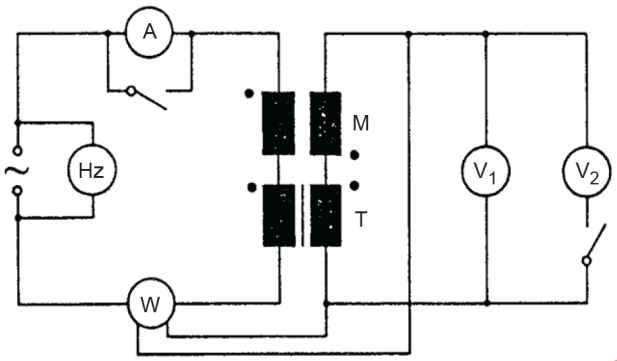
4.4 Air flux compensation

Compensation shall be made for the effect of air flux. This can be achieved, for example, by a mutual inductor M (see Figure 4). The primary winding of the mutual inductor is connected in series with the primary winding of the test apparatus, while the secondary winding of the mutual inductor is connected to the secondary winding of the test apparatus in series opposition.



Key

V_1 is the voltmeter that measures the average rectified voltage;

V_2 is the voltmeter that measures the RMS voltage;

A is the ammeter that measures the RMS value of the primary current;

Hz that measures the frequency;

W that measures the power;

M is the mutual inductor;

T is the test frame.

Figure 4 – Circuit for the determination of the specific total loss

The adjustment of the value of the mutual inductance shall be made so that when passing an alternating current through the primary windings in the absence of the test specimen in the test apparatus, the voltage measured between the non-common terminals of the secondary windings shall be no more than 0,1 % of the voltage appearing across the secondary winding of the test apparatus alone. Thus, the average value of the rectified voltage induced in the combined secondary windings is proportional to the peak value of the magnetic polarization in the test specimen.

NOTE 1 Alternatively, the air flux compensation can be executed by the numerical method (for details, see Annex D, Clause D.4).

NOTE 2 In the rest of this document, the term “compensated secondary voltage” is used to mean “voltage induced in the secondary winding compensated for the effect of air flux”.

4.5 Test specimen

The length of the test specimen shall be not less than 500 mm. Although the part of the test 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 width of the test specimen shall be as large as possible and at its maximum equal to the width of the yokes.

For ~~maximum~~ optimum accuracy, the minimum width shall be not less than 60 % of the width of the yokes.

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NOTE 1 Specific restrictions of the dimensions of the test specimens can be defined for special material grades in the respective product standards for magnetic materials.

NOTE 2 Information about application of the SST to strip samples of 50 mm to 250 mm width: Grain-oriented electrical steel used for distribution transformer (DT) cores is merchandized in the form of slit coils of 50 mm to 250 mm width cut from the as produced steel strips (parent coils) at the different positions across the original strips. The slit coils reflect the considerable variation of the material properties corresponding to the position on the original strip, where they have been cut from. These small strip specimens can be measured using this SST placing them side by side or with distributed gaps in the SST. In order to obtain a relevant measurement result, a minimum of 60 % of the 500 mm wide sample space needs to be filled with strips. The test strip samples can be taken successively from the start or the end of a slit coil. When preparing them taking care would avoid any damage which could influence the test result. Due to the cutting of the sheet into the small strips, the measured loss of narrow strips will be slightly increased compared to the original 500 mm.

The test specimen shall be cut without the formation of excessive burrs or mechanical distortion. The test specimen shall be plane. When a test specimen is cut, the edge of the parent ~~strip~~ coil is taken as the reference direction. ~~The following tolerances are allowed for~~ The angle between the direction of rolling and that of cutting shall not exceed:

±1° for grain oriented steel sheet;

±5° for non-oriented steel sheet.

For non-oriented steel sheet, two specimens shall be cut, one parallel to the direction of rolling and the other perpendicular unless the test specimen is square, in which case one test specimen only is necessary.

4.6 Power supply

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

In addition, the waveform of the compensated secondary ~~induced~~ voltage shall be maintained as sinusoidal as possible. ~~It is preferable to maintain~~ The form factor of the compensated secondary voltage shall be maintained to within ±1 % of 1,111. This can be achieved by various means, for example by using an electronic feedback amplifier or by a computational digital feedback system.

5 Determination of the specific total loss

5.1 Principle of measurement

The ~~single sheet tester~~ test apparatus with the inserted test specimen represents an unloaded transformer the total loss of which is measured by the circuit shown in Figure 4.

5.2 Apparatus

5.2.1 Voltage measurement

~~NOTE For the application of digital sampling methods, see Annex D.~~

5.2.1.1 Average type voltmeter

~~The secondary rectified voltage of the test apparatus~~ The average rectified value of the compensated secondary voltage shall be measured by an average type voltmeter. The preferred instrument is a digital voltmeter having an ~~accuracy~~ uncertainty of ±0,2 % or better.

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

The load on the secondary circuit shall be as small as possible. Consequently, the internal resistance of the average type voltmeter should be at least 1 000 Ω/V.

NOTE 2 For the application of digital sampling methods, see Annex D.

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5.2.1.2 RMS voltmeter

A voltmeter responsive to RMS values shall be used. The preferred instrument is a digital voltmeter having an ~~accuracy~~ uncertainty of ±0,2 % or better.

NOTE For the application of digital sampling methods, see Annex D.

5.2.2 Frequency measurement

A frequency meter having an ~~accuracy~~ uncertainty of ±0,1 % or better shall be used.

NOTE For the application of digital sampling methods, see Annex D.

5.2.3 Power measurement

The power shall be measured by a wattmeter having an ~~accuracy~~ uncertainty of ±0,5 % or better at the actual power factor and crest factor.

~~NOTE For the application of digital sampling methods, see Annex D.~~

The ohmic resistance of the voltage circuit of the wattmeter shall be at least 100 Ω/V for all ranges. If necessary, the losses in the secondary circuit shall be subtracted from the indicated loss value, see Formula (3) in 5.3.3.1.

The ohmic resistance of the voltage circuit of the wattmeter shall be at least 5 000 times its reactance, unless the wattmeter is compensated for its reactance.

If a current measuring device is included in the circuit, it shall be short-circuited when the secondary voltage is adjusted and the loss is measured.

NOTE For the application of digital sampling methods, see Annex D.

5.3 Measurement procedure of the specific total loss

5.3.1 Preparation of measurement

The length of the test specimen shall be measured with an ~~accuracy~~ uncertainty of ±0,1 % or better and its mass determined within ±0,1 %. The test specimen shall be loaded and centred on the longitudinal and transverse axes of the ~~test coil~~ windings, and the partly counterbalanced upper yoke shall be lowered.

Before the measurement, the test specimen shall be demagnetized by slowly decreasing an alternating magnetic field starting from well above the ~~value to be measured~~ knee of the magnetization curve of the test specimen material.

5.3.2 ~~Source setting~~ Adjustment of power supply

The ~~source~~ power supply output shall be ~~adjusted so that~~ slowly increased until the average rectified value of the compensated secondary ~~rectified~~ voltage, $|\overline{U_2}|$ has reached the required value. This value is calculated from the desired value of the magnetic polarization by means of:

$$|\overline{U_2}| = 4 f N_2 \frac{R_i}{R_i + R_t} A\hat{J} \quad (1)$$

where

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

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f is the frequency, in hertz;

R_i is the combined resistance of instruments in the secondary circuit, in ohms;

R_t is the series resistance of the secondary windings of the test apparatus and the mutual inductor, in ohms;

N_2 is the number of turns of the secondary winding;

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

$\hat{J}$ is the peak value of the magnetic polarization, in teslas.

The cross-sectional area A of the test specimen is given by the formula:

$$A = \frac{m}{l\,\rho_m} \tag{2}$$

where

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

l is the length of the test specimen, in metres;

ρ_m is the conventional density of the test material, or the value determined in accordance with IEC 60404-13, in kilograms per cubic metre.

5.3.3 Measurements

5.3.3.1 ~~The ammeter, if any, in the primary circuit shall be observed to ensure that the current circuit of the wattmeter is not overloaded. The ammeter shall then be short-circuited and the secondary voltage readjusted.~~ The primary current shall be checked to ensure that the current circuit of the wattmeter is not overloaded. If a current-measuring device is included in the circuit, it shall be short-circuited when the secondary voltage is adjusted and the loss is measured.

After checking that the waveform of the compensated secondary voltage stands within the required tolerances, the wattmeter shall be read. The value of the specific total ~~power~~ loss shall then be calculated from the formula:

~~$$P_s = \left[P \frac{N_1}{N_2} \frac{(1{,}111 |\overline{U_2}|)^2}{R_i} \right] \frac{l}{m\,l_m} \tag{3}$$~~

$$P_s = \left[P \frac{N_1}{N_2} - \frac{(\tilde{U}_2)^2}{R_i} \right] \frac{l}{m l_m} \tag{3}$$

Where P_s

$\tilde{U}_2$ is the ~~average~~ RMS value of the compensated secondary ~~rectified~~ voltage, in volts;

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

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

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

l_m is the conventional magnetic path length, in metres (l_m = 0,45 m);

l is the length of the test specimen, in metres;

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N_1 is the number of turns of the primary winding;

N_2 is the number of turns of the secondary winding;

R_i is the combined resistance of instruments in the secondary circuit, in ohms.

NOTE ~~1~~ Studies have shown that the inside length between the vertical inner faces of the limbs of the yokes is an appropriate mean value for the effective magnetic path length l_m for ~~different~~ various materials under test and polarization values [1][1].

~~NOTE 2 A long established practice in a few countries is to calibrate the test apparatus by determination of the effective magnetic path length based on specific total power loss measurements made in an Epstein frame. The details of the calibration procedure are described in annex B. This practice is permitted only for the evaluation of magnetic sheet and strip intended for consumption in those countries.~~

5.3.3.2 In the case of non-oriented ~~material~~ electrical steel, for values of the specific total loss specified in the product standards for magnetic materials, the reported value of the specific total loss shall be calculated as the average of the two measurement results obtained for the directions parallel and perpendicular to the direction of rolling. For other purposes, the values of the specific total loss parallel and perpendicular to the direction of rolling shall be reported separately.

5.3.4 Reproducibility of the measurement of the specific total loss

The reproducibility of this method using the test apparatus defined above is characterized by a relative standard deviation of 1 % (for detailed information on the source of this number see [2]) for grain-oriented electrical steel sheet and 2 % for non-oriented electrical steel sheet.

6 Determination of magnetic field strength, ~~excitation~~ primary current and specific apparent power

6.1 General

This Clause 6 describes measuring methods for the determination of the following characteristics:

– peak value of the magnetic polarization $\hat{J}$;

– RMS value of the primary current $\tilde{I}_1$;

– peak value of the magnetic field strength $\hat{H}$;

– specific apparent power S_s.

NOTE For the application of digital sampling methods, see Annex D.

6.2 Principle of measurement

6.2.1 Peak value of the magnetic polarization

The peak value of the magnetic polarization shall be derived from the average rectified value of the ~~rectified~~ compensated secondary voltage measured as described in 5.2.1.1.

6.2.2 RMS value of the ~~excitation~~ primary current

The RMS value of the ~~excitation~~ primary current shall be measured by an RMS ammeter in the circuit of Figure 5.

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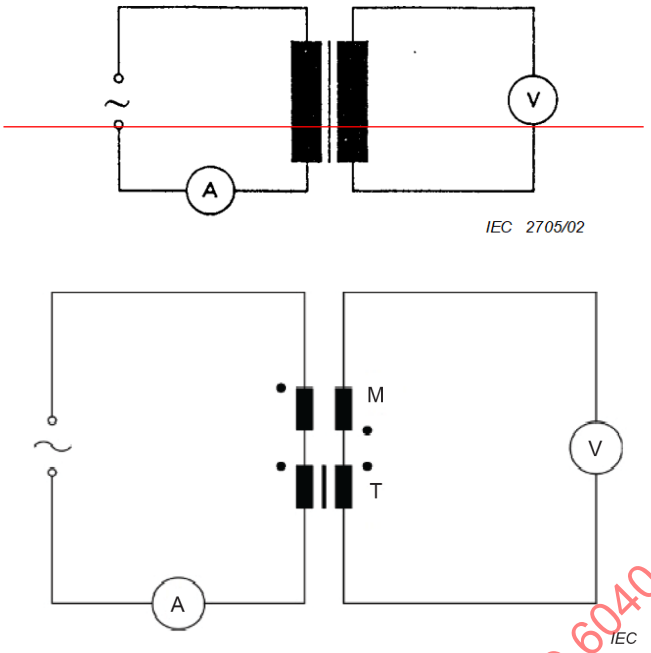
[1] Numbers in square brackets refer to the Bibliography.



Key

V is the voltmeter that measures the average rectified voltage;

A is the ammeter that measures the RMS value of the primary current;

M is the mutual inductor;

T is the test frame.

Figure 5 – Circuit for measuring the RMS value of the ~~excitation~~ primary current

6.2.3 Peak value of the magnetic field strength

The peak value of the magnetic field strength shall be obtained from the peak value $\hat{I}$ of the primary current. This shall be determined by measuring the voltage drop across a known precision resistor ~~R_n~~ R as described in 6.3.5 using ~~a peak~~ an electronic voltmeter of high sensitivity indicating the peak value as shown as V_2 in Figure 6.

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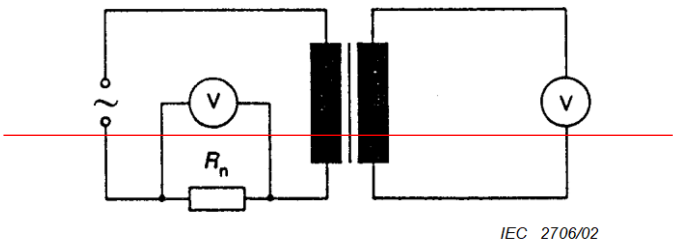

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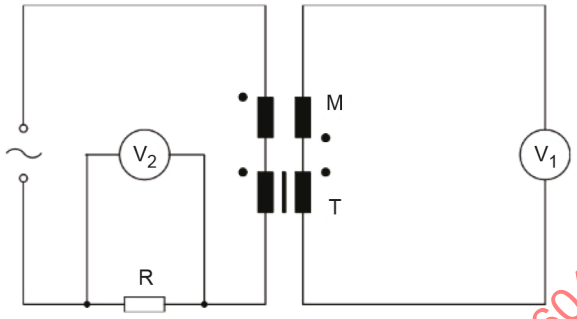

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Key

V_1 is the voltmeter that measures the average rectified value of the compensated secondary voltage;

V_2 is the voltmeter that measures the peak value (or the RMS value, see 6.3.2) of the voltage drop across the non-inductive precision resistor;

R is the non-inductive precision resistor;

M is the mutual inductor;

T is the test frame.

Figure 6 – Circuit for measuring the peak value of the magnetic field strength

6.3 Apparatus

6.3.1 Average type voltmeter

~~The secondary rectified voltage of the test apparatus shall be measured by an average type voltmeter. The preferred instrument is a digital voltmeter having an accuracy of ±0,2 %.~~

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

~~The load on the secondary circuit shall be as small as possible. Consequently, the internal resistance of~~ The average type voltmeter should be at least 1 000 Ω/V.

The average type voltmeter shall be in accordance with 5.2.1.1.

6.3.2 RMS current measurement

The RMS value of the primary current shall be measured either by means of an RMS ammeter of low impedance of class 0,5 or better (see Figure 5), or by using a precision resistor and an RMS ~~electronic~~ voltmeter described in 5.2.1.2 (see Figure 6, in this case the peak voltmeter is to be replaced by an RMS voltmeter).

6.3.3 Peak current measurement

The measurement of the peak voltage across the resistor ~~R_n~~ R (see Figure 6) shall be achieved either by means of an electronic voltmeter of high sensitivity indicating the peak value, or by means of a calibrated oscilloscope.

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~~The full scale error of the device used shall be ±3 % or better.~~

A peak voltmeter having an uncertainty of ±0,5 % or better shall be used.

6.3.4 Power supply

The power supply shall be in accordance with 4.6.

6.3.5 Resistor ~~R_n~~ R

The method shown in Figure 6 requires a precision non-inductive resistor R of a value known to within ±~~0,5~~ 0,1 %.

~~The resistance value to be chosen depends upon the sensitivity of the peak voltmeter. It shall not exceed 1 Ω in order to minimize the distortion of the induced voltage waveform.~~

The resistance value of the resistor R shall not exceed 1 Ω in order to minimize the distortion of the magnetizing voltage and, thus, to facilitate the sinusoidal waveform of the induced secondary voltage.

6.4 Measuring procedure

6.4.1 Preparation for measurement

The length of the test specimen shall be measured with an ~~accuracy~~ uncertainty of ±0,1 % or better and its mass shall be determined with an uncertainty of ±0,1 % or better. The test specimen shall be loaded and centered on the longitudinal and transverse axes of the ~~test~~ windings coil. The partly counterbalanced upper yoke shall then be lowered.

Before the measurement, the test specimen shall be demagnetized by slowly decreasing an alternating magnetic field starting from well above the ~~value to be measured~~ knee of the magnetization curve of the test specimen material.

6.4.2 Measurement

In practice, single values or groups of peak values of the magnetic polarization $\hat{J}$ and the magnetic field strength ($\hat{H}$ or $\tilde{H}$) are determined.

If the peak value of the magnetic field strength is specified and the peak value of the magnetic polarization is to be determined, the primary current shall be set to give the relevant magnetic field strength (see below). Then the compensated secondary voltage of the ~~single sheet tester~~ test apparatus shall be read on the average type voltmeter (see 5.2.1.1).

Again, if the peak vale of the magnetic polarization is specified and the peak value of the magnetic field strength is to be determined, the secondary voltage shall be set to its specified value as described in 5.3.2.

For the determination of $\tilde{H}$, the RMS value of the primary current shall be read on the RMS ammeter according to the circuit of Figure 5 or on the RMS voltmeter according to the circuit of Figure 6.

For the determination of $\hat{H}$, the peak value of the voltage drop across resistor ~~R_n~~ R shall be read on the peak voltmeter or the calibrated oscilloscope.

6.4.3 Non-oriented material

In the case of non-oriented material, for the peak value of the magnetic polarization $\hat{J}$ at the peak value of the magnetic field strength $\hat{H}$ specified in the product standards for magnetic

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materials, the reported value of $\hat{J}$ shall be calculated as the average over the two measurement results obtained for the directions parallel and perpendicular to the direction of rolling. For values of $\hat{J}$ for other purposes and for the measurement of the specific apparent power and the RMS value of ~~excitation~~ the primary current, the values obtained for the directions parallel and perpendicular to the direction of rolling shall be reported separately.

6.5 Determination of characteristics

6.5.1 Determination of $\hat{J}$

6.5.1.1 Peak value $\hat{J}$ of the magnetic polarization

~~The peak value of the magnetic polarization is given by the equation:~~

$$\hat{J} = \frac{1}{4 f N_2 A} \overline{|U_2|} \quad (4)$$

~~To obtain $\overline{|U_2|}$, the voltmeter reading shall be corrected by the factor:~~

$$\frac{R_v + R_2}{R_v}$$

~~where~~

~~$\hat{J}$ is the peak value of the magnetic polarization, in tesla;~~

~~f is the frequency, in hertz;~~

~~N_2 is the number of turns of the secondary winding;~~

~~A is the cross-section of the test specimen, in square metres;~~

~~R_v is the voltmeter internal resistance, in ohms;~~

~~R_2 is the resistance of the secondary winding, in ohms;~~

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

The peak value of the magnetic polarization is given by the formula:

$$\hat{J} = \frac{1}{4 f N_2 A} \frac{R_i + R_t}{R_i} \overline{|U_2|} \quad (4)$$

where

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

f is the frequency, in hertz;

N_2 is the number of turns of the secondary winding;

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

R_i is the combined resistance of instruments in the secondary circuit, in ohms;

R_t is the series resistance of the secondary windings of the test apparatus and the mutual inductor, in ohms;

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

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6.5.1.2 Reproducibility of $\hat{J}$

The reproducibility of this method using the test apparatus defined above is characterized by a relative standard deviation of 0,25 %.

6.5.2 Determination of $\tilde{H}$

The RMS value of the magnetic field strength shall be calculated from the RMS value of the primary current indicated by the RMS ammeter ~~according to~~ in the circuit of Figure 5 or by ~~the~~ the RMS voltmeter ~~according to~~ in the circuit of Figure 6 as described in 6.3.2:

$$\tilde{H} = \frac{N_1}{l_m} \tilde{I}_1 \tag{5}$$

where

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

N_1 is the number of turns of the primary winding;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,45 m);

$\tilde{I}_1$ is the RMS value of primary current, in amperes.

NOTE After several groups of corresponding values of $\tilde{J}$ and $\tilde{H}$ have been determined, the magnetization curve of $\tilde{J}$ against $\tilde{H}$ can be drawn.

6.5.3 Determination of $\hat{H}$

The peak value of the magnetic field strength shall be calculated from the ~~reading~~ peak value of the primary current $\hat{U}_m / R_n$ indicated by the peak voltmeter in the circuit of Figure 6 as described in 6.3.3:

$$\hat{H} = \frac{N_1}{R_n l_m} \hat{U}_m \tag{6}$$

where

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

R_n is the resistance value of the non-inductive precision resistor R in Figure 6, in ohms;

$\hat{U}_m$ is the peak voltage drop across ~~R_n~~ resistor R, in volts.

NOTE 1 The amplitude permeability is expressed as:

$$\mu_a = \frac{\hat{J}}{\mu_o \hat{H}} + 1$$

NOTE 2 After several groups of corresponding values of $\hat{J}$ and $\hat{H}$ have been determined, the magnetization curve of $\hat{J}$ against $\hat{H}$ can be drawn.

6.5.4 Determination of S_s

The apparent power is given by:

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$$S = \tilde{I}_1 \bullet \tilde{U}_2 \bullet \frac{N_1}{N_2} = \tilde{I}_1 \bullet 1{,}111 \bullet \overline{|U_2|} \bullet \frac{N_1}{N_2} \tag{7}$$

where

S is the apparent power, in voltamperes;

$\tilde{U}_2$ is the RMS value of secondary voltage of the single sheet tester, in volts.

NOTE The relation $\tilde{U}_2 = 1{,}111 \cdot \overline{|U_2|}$ is valid only for sinusoidal voltage.

Division of this quantity by the effective mass of the test specimen $m_a = \frac{l_m}{l} m$ gives the specific apparent power:

$$S_s = \frac{S}{m_a} = \frac{\tilde{I} \cdot 1{,}111 \cdot \overline{|U_2|} l N_1}{m l_m N_2} \tag{8}$$

where

S_s is the specific apparent power, in voltamperes per kilogram;

l is the length of the test specimen, in metres;

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

m_a is the effective mass of the test specimen; in kilograms

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

N_1 is the number of turns of the primary winding;

N_2 is the number of turns of the secondary winding;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,45 m);

$\tilde{I}_1$ is the RMS value of primary current, in amperes.

6.5.5 Reproducibility of the measurement of the specific apparent power

The reproducibility of this method using the test apparatus defined above is characterized by a relative standard deviation of 3 % or less.

7 Test report

The test report shall include the following, as applicable:

a) the type and identity of test specimen;
b) the density of material (conventional or as determined in accordance with IEC 60404-13)
c) the length and width of test specimen;
d) the ambient temperature of measurement;
e) the measurement frequency;
f) the peak values of the magnetic polarization or the magnetic field strength;
g) the results of the measurements.

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Annex A
(normative)

Requirements concerning the manufacture of yokes

~~It is important to ensure that the loss in the yokes is low and constant. A loss of 1 mW/kg at a magnetic flux density of 40 mT is typical, measured at a frequency of 50 Hz. One of the Ways in which losses can become high is due to short circuits between laminations in the yoke. For the measurement of the power loss in the yokes a primary and a secondary winding wound on the yokes may be used; 25 turns are sufficient for each of these windings.~~

~~It is necessary to test the interlaminar resistance between parts of the yoke by use of an ohmmeter and probes.~~

It is important to ensure that the power loss dissipated by the yokes is stable and small compared with the total power loss dissipated by the specimen. A power loss of 1 mW/kg at a magnetic flux density of 40 mT or of 0,1 mW/kg at 10 mT are typical, measured at a frequency of 50 Hz (see Figure B.1 and Table B.1). Ways in which the loss can become high are short circuits between laminations in the yokes and uneven distribution of the magnetic flux inside the yokes. For the measurement of the power loss dissipated by the yokes, a primary and a secondary winding wound on the yokes or on appropriate formers shall be used. Four sets of outer primary and inner secondary windings shall be arranged symmetrically on the four vertical limbs of the yokes and switched in series connection. The number of turns depends on the configuration of the measurement instruments. As a typical case. the number of 25 turns for each sub-winding was found to work properly. The windings shall be disconnected when not used for the yokes' loss measurement.

During the manufacture of the yokes with stacked lamination, a stress relief annealing of the cut strips is required. After bonding the material to build the yokes (which shall be done without application of high pressure), the pole faces shall be machined. Parallelism shall be proven with an appropriate gauge, and the uniformity of the air gap checked using engineer's blue. Further grinding in stages using carborundum and diamond paste will probably be necessary until a uniform distribution of the engineer's blue indicates a sufficiently homogeneous air gap. The grinding can be carried out by putting the upper yoke in the normal position of use on top of the bottom yoke and moving it to and fro through a small distance.

With wound cut C-cores corresponding measures shall be taken so that equivalent performance characteristics are achieved.

The process of grinding causes the metal to flow between laminations and produces short circuits. It is important to remove this flowed metal by a careful acid etching process using a non-oxidizing acid (e.g. hydrochloric acid). This consists in rubbing the pole faces with an acid-soaked cloth until the flowed layer is removed. It is important to carefully ~~wash and neutralize the steel~~ neutralize and wash away the acid remaining on the pole faces and between the laminations.

It is helpful to measure the yoke's loss before and after grinding and etching to verify that the loss has been reduced by this treatment.

~~A final check on interlaminar insulation shall be made after pole face etching and cleaning.~~

A thorough check of the inter-laminar insulation of the yokes with stacked lamination shall be made after pole face etching and cleaning. The electrical resistance of the laminations of the upper and the bottom yokes shall be measured separately. The resistance of all the 10 sections, 5 cm long each, along the pole faces of the yokes shall be measured using a contact pattern strip (see, for instance, Figure 3 in [2]) and an ohmmeter with an uncertainty of 1 % or better. For monitoring that the transition resistance at each contact is negligible, the resistance measurements shall be expanded over all groups of two neighbouring 5-cm sections, i.e. over

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all section pairs 10 cm in length. The resistance value of the 10-cm section pairs shall agree within 5 % with the sum of the two resistance values measured separately over the respective two 5-cm sections. For proper contact, it is recommended to apply a thin strip of slightly compressible non-conductive material under the contact strip (correspondingly, on top of the contact strip when measuring the bottom yoke). The measurements can be made at the air gap of the front side while the rear side air gap shall be equipped with a strip of isolating material. For the measurements, the upper yoke shall be set down on the lower yoke.

The resistance value of each 5-cm section of both yokes shall be 10 Ω at least. This minimum value was found with the high quality yokes in the series studied in the exercise shown in Figure 4 of IEC TR 62981:2017 [2]. The resistance measured between the outermost laminations of the yokes (over the full length of 50 cm) is then 100 Ω at least. For the case of wound cut C-core yokes it is estimated that, correspondingly, the resistance measured between the outermost laminations shall be again not less than 100 Ω:Thus, the outermost eddy current path encloses the same magnetic flux in both cases of lamination type.

The inspection of the yokes shall be documented by the manufacturer of the measurement set-up in a detailed record.

NOTE Details of how to measure the resistivity of the yokes' 5-cm sections are given in IEC TR 62981 [2].

Before use, the yokes shall be carefully demagnetized from a magnetic flux density well above ~~the highest magnetic flux density which would occur in the yokes during use~~ the knee of the magnetization curve of the yoke material. The windings for the yokes' loss measurement can be used for the demagnetizing. The power loss dissipated by the yokes at the magnetic polarization which would occur inside the yokes during use shall be measured and recorded by the manufacturer of the SST set-up in the course of the mandatory quality check of the yokes before delivery.

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Annex B
(informative)

Calibration of the test apparatus with respect to the Epstein frame

NOTE This annex does not form part of the requirements of the standard. It is included for information for those who wish to obtain the correlation between measurements taken by this method and the Epstein frame method (see note 2, page 19).

The calibration of the test apparatus consists in the determination of the effective length of its magnetic circuit from the measurement of the specific total loss in the Epstein frame.

This determination of the effective length of the magnetic circuit is made for each grade of material and each magnetic flux density for which the specific total power losses are to be determined.

Firstly the specific total power losses are measured by means of an Epstein frame in accordance with IEC 60404-2 (except that, in the case of non-oriented material, all the strips loaded in the Epstein frame shall be of the same orientation).

Then, at least 12 strips which have already been measured in the Epstein frame shall be placed side by side in the test apparatus. The losses are measured again by the apparatus for a magnetic flux density identical to that used in the determination of the specific total power loss in the Epstein frame.

The effective length l_m of the magnetic circuit is then calculated in accordance with the equation:

$$l_m = \frac{P\,l}{m P_{sE}} \qquad \text{(B.1)}$$

where

P is the power measured by the wattmeter connected with the test apparatus, in watts;

l is the length of the Epstein strips, in metres;

m is the total mass of Epstein strips placed in the test apparatus, in kilograms;

P_{sE} is the specific total power loss determined by the Epstein frame, in watts per kilogram.

NOTE In the case of non-oriented materials, there will be two effective path lengths: one for each direction of sampling.

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Annex B
(informative)

Check and verification of reliable performance of the SST set-up by the use of reference samples and impact of the loss dissipated in the yokes

The continuous checking of the performance reliability of a SST set-up is recommended to be properly managed by the use of reference samples. This is particularly relevant with test specimens of high permeability materials which are most sensitive with regard to performance alterations of the set-up. It is recommendable that the laboratory has a set of reference samples to their disposal which represents the properties of the materials the set-up is mostly used for.

It is also recommended to provide reference samples with magnetic properties certificated by standards laboratories that have taken part to the latest IEC round robin tests [2] and are able to trace the sample's magnetic characteristics to the results of that RRT, or by laboratories having a specific accreditation.

If conspicuous deviation from expected values appear which also are reproduced when applying a reference sample of known magnetic characteristics, a check of the electrical measuring part of the set-up should additionally be made using appropriate means, for instance a calibrated double signal generator delivering certified electrical power values in the relevant measurement range.

The systematic error of the SST method is formed by the magnetic loss dissipated in the flux closing yokes (see 4.3.1). Its relative contribution to the measured loss value depends on the flux density, grade and thickness of the specimen under test and amounts to about 2 % for high quality electrical steel sheets at 1,7 Tesla. To benchmark this relative to Epstein frames' performance, it is noted that, roughly, the SST measures the specific total loss too high by 2 % and the Epstein frame too low by 4 % (see also [2]).

Studies on the performance of three standard yoke systems (Figure 1), two with a stacked lamination (SST1 and SST3) and one with wound C-cut core lamination (SST2) were made at the German standard institute PTB [3] in 1990. The measurement results are shown in Figure B.1 supplemented by Epstein measurements in the upper region made at IENGF by G. Bertotti [4]. They present the loss dissipated by various yokes systems and corresponding Epstein measurements in the low flux density region which reflect the situation in the yokes under test conditions.

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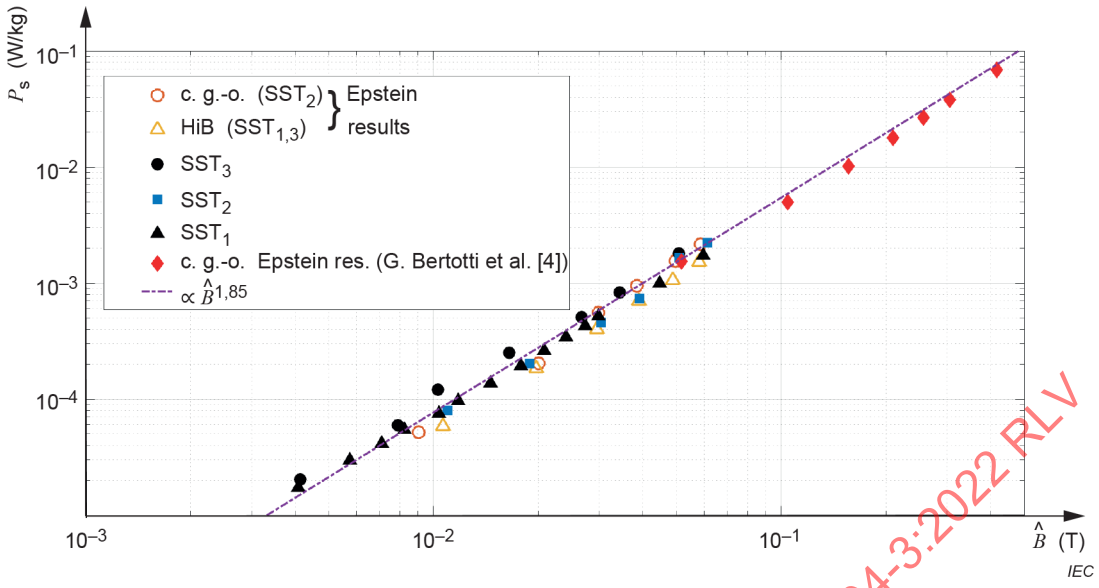

Figure B.1 – Specific total loss vs. peak flux density (after J. Sievert [3] and G. Bertotti [4]); straight line: $P_S \propto B^{1.85}$ approximation (after C. Ragusa).

It can be seen that the three yoke systems, including the wound C-cut core type, show agreement within a certain statistical dispersion. The Epstein results of corresponding S-type (c.g.-o.) and P-type (HiB) grain-oriented material are located - also G. Bertotti's results in the upper part - a bit below the yokes' results. Generally it appears that, in the very low flux density region, the performance of different yokes systems is equalized because the magnetizing processes are dominated by domain wall bowing without excess loss production as also can be concluded from the zero Barkhausen noise in that region. These phenomena could also explain the amazing agreement of performance of a variety of 10 yokes within the IEC RRT (2013/2014) [2]. Moreover, in line with this picture are the findings reported by SST manufacturers, that strong loss variation between yokes made of different materials in the 1.0 T to 1.7 T region are not reflected in the 10 mT region, i.e. the variations in high flux region appear to be not really relevant to the yokes' quality under the relevant test conditions.

The measured loss characteristic of yoke loss values for the relevant flux densities allow to determine the relative contribution of the yokes, p_Y:

$$p_Y = \frac{P_Y}{P_{Sp}} \tag{B.1}$$

where

P_Y is the power loss dissipated by the yokes under test conditions, in watts;

P_{Sp} is the total loss of the model specimen at 1,7 T, in watts.

Table B.1 shows 5 examples of grades and their relevant quantities under test conditions at 1,7 T using the data given in Figure B.1. They demonstrate the contribution of the yokes to the measured value of the total specific loss.

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Table B.1 – Loss dissipated by the yokes of a standard SST, determined from the loss curves measured on 3 yoke pairs as shown in Figure B.1, and relevant quantities including the relative yokes' contribution, p_Y; exemplified using 5 standard grades

Steel name (examples of grades)	Nominal thickness of specimen, d	Nominal Loss, P_{sp} of modelling specimen at 1,7 T	Flux density $\hat{f}_y$ of yokes at 1,7 T of specimen	Specific total loss in yokes at 1,7 T of specimen	Total loss in yokes, P_Y at 1,7 T in the specimen	Relative contribution of the yokes $p_Y = P_Y/P_{Sp}$
	mm	W	T	W/kg	W	(x100), %
M130-30S5	0,30	0,658	0,010 2	0,000 085	0,011	1,7
M100-27P5	0,27	0,456	0,009 2	0,000 068	0,008 8	1,9
M90-23P5	0,23	0,349	0,007 8	0,000 050	0,006 5	1,9
M80-23P5	0,23	0,310	0,007 8	0,000 050	0,006 5	2,1
M70-20P5	0,20	0,236	0,006 8	0,000 040	0,005 2	2,2

The subtraction of the yokes' power loss will effectuate that the result approaches the physical true value of loss. However, it should be taken into account that the method is afflicted with considerable indeterminacy due to the imperfectness of the model used at the air gap region and the difficult measurement condition in the low flux region. The uncertainty of this correction procedure is estimated to amount to 10 % to 20 % of the correction (error of error).

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Annex C
(informative)

Epstein to SST relationship for grain-oriented steel sheet

NOTE This Annex C does not form part of the requirements of this document. It is included for information for those who wish to convert SST values into Epstein values and vice versa. It should be noted that the determination of the Epstein/SST ratio usually shows a considerable dispersion from sample-to-sample pair even for identical grades. In fact, this was the reason for defining an SST method independent from the Epstein method (changing SST(1982) to SST (1992)).

There are two significant differences from the procedure in annex B as follows:

– annex B prescribes the procedure of the calibration of an SST by means of long Epstein strips. It yields an exact value for the Epstein/SST calibration factor for the individual sample under consideration;

– by cutting the sheets into strips, the procedure of annex B yields an Epstein/SST calibration factor which refers to a stress-free sheet sample which is formed from the annealed Epstein strips. When using this calibration procedure, specific total loss values determined for sheet specimens will agree more closely with those determined using corresponding Epstein specimens if the sheet specimens are stress free, and will differ more from Epstein values if the sheets are not stress free.

Annex C, on the other hand, describes the conversion of SST to Epstein values and vice versa in general, i.e. where only one of the two methods of measurements has been performed. Annex C is restricted to grain-oriented material. Of course, the general validity of the presented relationships is subject to the larger uncertainty of the conversion, because the statistical scatter due to the internal stress, etc. of the individual sheet sample is considerable. This amounts to about ±2 % (for the whole range of $\hat{J}$) for the specific total loss, P, from about ±3 % (at $\hat{J}$ = 1,3 T) to ±10 % (at 1,7 T) for the field strength quantities, H, and from about ±5 % (at 1,3 T) to ±20 % (at 1,7 T) for the specific apparent power, S [1] and [2].

This Annex C describes the conversion of SST to Epstein values and vice versa in general, i.e. where only one of the two methods of measurements has been performed. The general validity of the presented relationships is restricted because it is subject to larger uncertainty of the conversion due to the statistical scatter through the varying internal stress of the individual sheet samples and, even more relevant, through the considerable scattering of the Epstein strip samples preparation with GO materials. The dispersion of the presented relative SST- Epstein difference results δP amounts to about ±2 % (for the whole range of $\hat{J}$) for the specific total loss, P_s, from about ±2 % (at $\hat{J}$ = 1,3 T) to ±10 % (at 1,7 T) for the field strength quantities, H, and from about ±5 % (at 1,3 T) to ±20 % (at 1,7 T) for the specific apparent power ([5] and [6]). The dispersion (uncertainty) values are also a rough estimation only because the scatter is not normally distributed. Thus, to avoid misunderstanding, it was abstained from indicating error bars in the diagrams.

The relationships were achieved on the basis of Epstein and SST measurements on about 750 740 samples of the most significant S-type grain-oriented grades, supplied by eight different manufacturers and taken from different production runs. For further details see [5] and [6]. This study did not include domain-refined materials. However, it is the decision of the user of this standard whether or not to apply annex C to domain-refined materials. This study did include very few of high permeability (P) grades which did not show specific performance.

This informative Annex C is not applicable to the new group of R-type domain-refined (RD) materials for which, after intense discussions on this issue, a specific SST to Epstein conversion factor F_c = 0,925 at $\hat{J}$ = 1,7 T was introduced [7]. Transformer designers report that they also apply the findings presented in this Annex C to the design of transformers using non domain-refined P-type materials.

The relationship between Epstein and SST results can be described by a factor the relative differences (in %) δP (for the specific total loss, P) and δHS (for the magnetic field strength, H

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and the specific apparent power, S). The conversion of Epstein results, $P_{s,EPS}$, H_{EPS} and $S_{s,EPS}$, to SST results, $P_{s,SST}$, H_{SST} and $S_{s,SST}$, can be carried out using the following formulas:

$$P_{s,SST} = P_{s,EPS} \times (1 + \delta P/100) \quad \text{(C.1)}$$

$$H_{SST} = H_{EPS} \times (1 + \delta HS/100) \quad \text{(C.2)}$$

$$S_{s,SST} = S_{s,EPS} \times (1 + \delta HS/100) \quad \text{(C.3)}$$

Correspondingly, the conversion in the reverse direction can be carried out ~~as follows~~ using the inverse of Formulae C.1, C.2 and C.3 resulting in Formulae C.4, C,5 and C.6:

$$P_{s,EPS} = P_{s,SST} / (1 + \delta P/100) \quad \text{(C.4)}$$

$$H_{EPS} = H_{SST} / (1 + \delta HS/100) \quad \text{(C.5)}$$

$$S_{s,EPS} = S_{s,SST} / (1 + \delta HS/100) \quad \text{(C.6)}$$

NOTE The relation between the Conversion Factor F_C and δP is given by the formula $F_C = 1/(1+\delta P/100)$.

The ~~conversion factors~~ averaged relative differences as determined from the experiments (see reference [5] and [6]) are shown as rhombus symbols in the diagrams of Figure C.1 for δP and Figure C.2 for δHS. The values for ~~J =~~ $\hat{J}$, 1,0 T to 1,2 T, were obtained by extrapolation from the experimental data. The two diagrams also comprise the curve fits to the experimental data (continuous lines). The relationships representing the curve fits are as follows:

$$\delta P = 1{,}46 + 0{,}242 \hat{J}^5 \quad \text{(C. 7)}$$

$$\delta HS = 6{,}0 + 0{,}103 \hat{J}^{10} \quad \text{(C.8)}$$

~~When J exceeds 1,8 T, equations (C.2a-c) and (C.3a,b) or a graphical extrapolation may be applied.~~

~~The conversion factors as obtained from equation (C.3a) and (C.3b) are presented in table C.1.~~

The relative differences as obtained from Formulae (C.7) and (C.8) and the related conversion factor are presented in Table C.1. As remarked above, the values aim first and foremost at S-type grain-oriented grades, however, the application to non-domain refined P-grade materials has also been reported.

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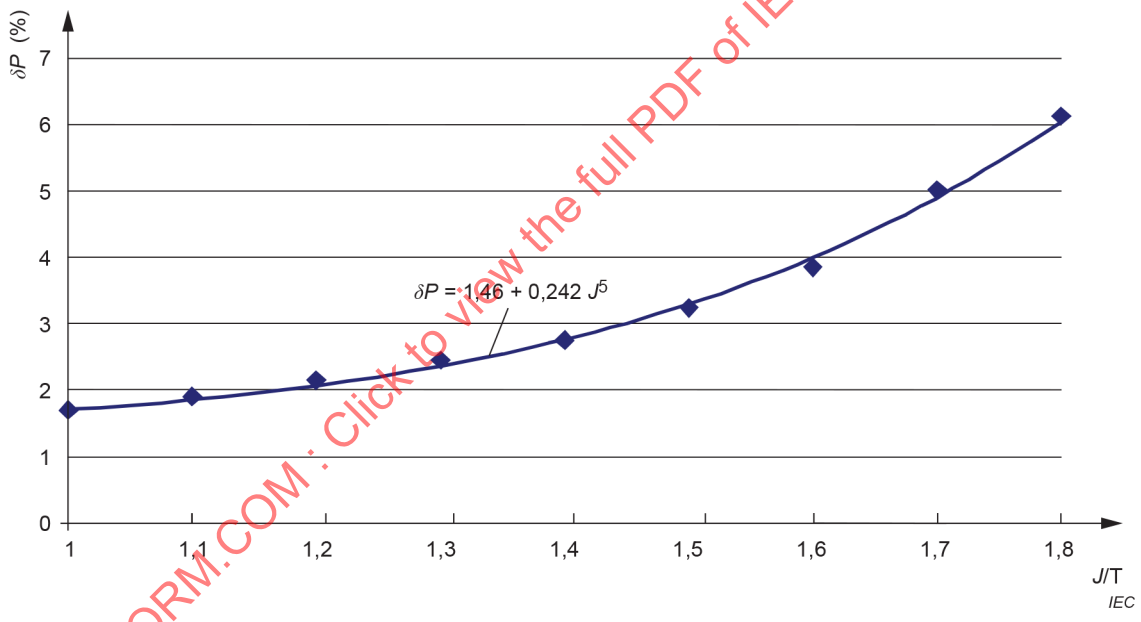
Table C.1 – ~~Epstein-SST conversion factors *δP* and *δHS*~~ SST-Epstein relative differences *δP* and *δHS* and the conversion factor F_C for conventional grain-oriented material in the polarization range 1,0 T to 1,8 T

~~*J*~~ $\hat{J}$	*δP*	*δHS*	$F_C = 1/(1+\delta P/100)$
T	%	%	
1,0	1,7	6,1	0,983
1,1	1,8	6,3	0,982
1,2	2,1	6,6	0,979
1,3	2,4	7,4	0,977
1,4	2,8	9,0	0,973
1,5	3,3	12	0,968
1,6	4,0	17	0,962
1,7	5,0	27	0,952
1,8	6,0	43	0,943



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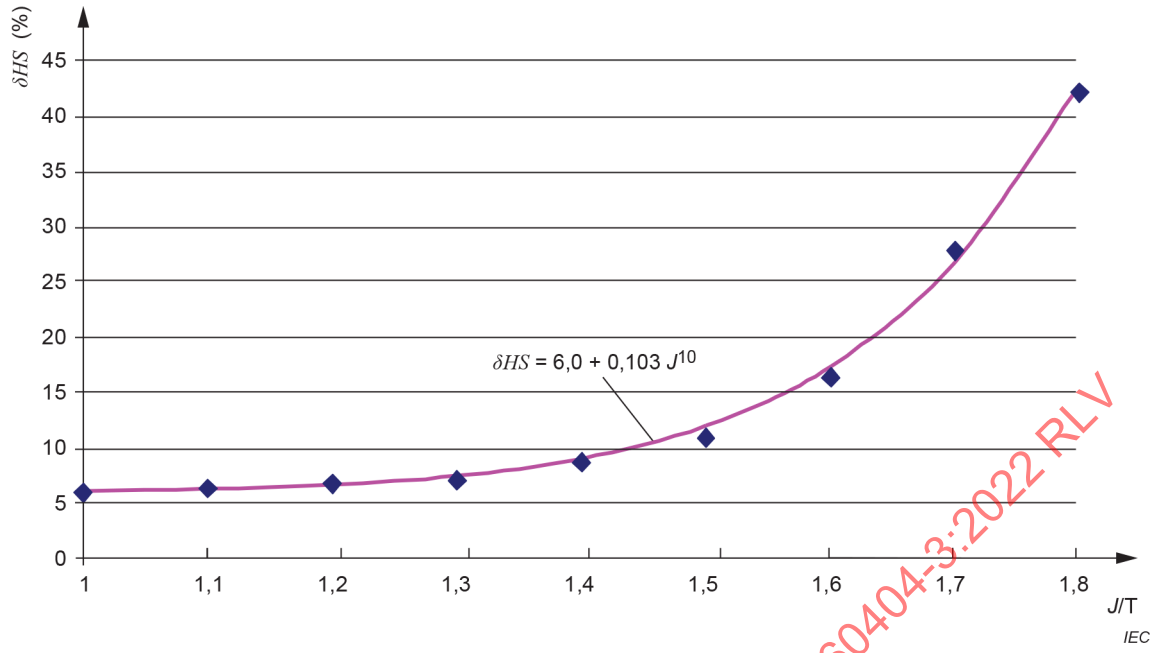
Key

Rhombus symbols = experimental data (values at 1,0 T to 1,2 T were extrapolated using the measured values)

Continuous line = curve fit to the experimental data according to Formula (C.7)

Figure C.1 – ~~Epstein-SST conversion factor *δP*~~ SST-Epstein relative difference *δP* for conventional grain-oriented material versus magnetic polarization ~~*J*~~ $\hat{J}$



Key

Rhombus symbols = experimental data (values at 1,0 T to 1,2 T were extrapolated using the measured values).

Continuous line = curve fit to the experimental data according to formula (C.8).

Figure C.2 – ~~Epstein SST conversion factor *δHS*~~ SST-Epstein relative difference *δHS* for conventional grain-oriented material versus magnetic polarization ~~*J*~~ *Ĵ*

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Annex D
(informative)

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

D.1 General

The digital sampling method is an advanced technique that is becoming almost exclusively applied to the electrical part of the measurement procedure of this document. It is characterized by the digitalization of the compensated secondary voltage, $U_2(t)$, the voltage drop across the non-inductive precision resistor in series with the primary winding (see Figures 4 and 6), $U_1(t)$, and the evaluation of the 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_{1j} respectively, are sampled and held simultaneously from the time-dependent voltage functions during the narrow and equidistant time periods 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 specimen 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.

The digital sampling method may be applied to the measurement procedures which are described in the main part of this document. The block diagram in Figure 4 applies equally to the analogue methods and the digital sampling method, the digital sampling method allows all functions of the measurement equipment in Figure 4, Figure 5 and Figure 6 to be realized by a combined system of a data acquisition equipment and software. The control of the sinusoidal waveform of the 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 D and are not treated here. More information can be found in [8] and [9].

This Annex D is helpful in understanding the impact of the digital sampling method on the precision achievable by the methods of this document. This is particularly important because ADC circuits, transient recorders and supporting software are easily available thus encouraging one to build one's own wattmeter. The digital sampling method can offer low uncertainty, but it leads to large errors if improperly used.

D.2 Technical details and requirements

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

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

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 seconds.

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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 [10] and the sampling frequency, f_s, should be greater than twice the higher order harmonic of the input signal ~~bandwidth~~ (Nyquist-Shannon condition [10]).

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:

$$\hat{J} = \frac{1}{4fN_2A}\frac{1}{T}\int_{t=0}^{T}\left|U_2(t)\right|dt \cong \frac{1}{4f_sN_2A}\sum_{j=0}^{n-1}\left|u_{2j}\right| \tag{D.2}$$

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

~~$$P_s = \frac{N_1}{l_m R N_2 A \rho_m}\frac{1}{T}\int_{t=0}^{T}U_1(t)U_2(t)dt \cong \frac{N_1}{l_m R N_2 A \rho_m}\frac{1}{n}\sum_{j=0}^{n-1}u_{1j}u_{2j}$$~~

$$P_s = \frac{1}{l_m A \rho_m}\left(\frac{N_1}{R_n N_2}\frac{1}{T}\int_{t=0}^{T}U_1(t)U_2(t)dt - \frac{\tilde{U}_2^{\,2}}{R_i}\right) \cong \frac{1}{l_m A \rho_m}\left(\frac{N_1}{R_n N_2}\frac{1}{n}\sum_{j=0}^{n-1}u_{1j}u_{2j} - \frac{1}{R_i}\frac{1}{n}\sum_{j=0}^{n-1}u_{2j}^{\,2}\right) \tag{D.3}$$

where

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

P_s is the specific total loss of the specimen, in watts 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_1 is the number of turns of the primary 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;

~~R~~R_n is the resistance of the non-inductive precision resistor R in series with the primary winding (see Figure 6), in ohms;

U_1 is the voltage drop across the non-inductive precision resistor R, in volts;

[2] The peak value of the magnetic field strength and the apparent power can be calculated correspondingly by using

~~$\hat{H} = \frac{N_1}{Rl_m}\hat{U}_1$~~ $\hat{H} = \frac{N_1}{R_n l_m}\hat{U}_1$

and ~~$S_s \cong \frac{N_1}{l_m R N_2 A \rho_m}\sqrt{\frac{1}{n}\sum_{j=0}^{n}u_{1j}^{\,2}}\sqrt{\frac{1}{n}\sum_{j=0}^{n}u_{2j}^{\,2}}$~~ $S_s \cong \frac{N_1}{l_m R_n N_2 A \rho_m}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}u_{1j}^{\,2}}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}u_{2j}^{\,2}}$

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U_2 is the secondary voltage, in volts;

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

j is the index of instantaneous values;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,45 m~~; for measurements in connection with a calibration by means of Epstein measurements, see Annex B~~);

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

R_i is the combined resistance of the instruments in the secondary circuit, in ohms;

$\tilde{U}_2$ is the RMS value of the voltage induced in the secondary winding, in volts.

The pairs of values, u_{2j} and u_{1j}, 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, $U_1(t)$ 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 [11]. 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 must 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 (for instance at 400 Hz which is within the scope of this document). The use of a low-pass anti-aliasing filter [10] 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 [11,12] have shown that below a 12-bit resolution, the digitalization 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 phase shift should be small enough so that the power measurement uncertainty specified in this document, namely 0,5 %, is not exceeded. The consideration of the phase shift is more relevant the lower the power factor $\cos(\varphi)$ becomes (φ being the phase shift between the fundamental components of the two voltage signals). For this reason, the concept of a single channel with multiplexer leading to different sampling times for the instantaneous values of the two voltages is not to be recommended.

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.

D.3 Calibration aspects

The verification of the repeatability and reproducibility requirements of this document make careful calibration of the measurement equipment necessary. The two voltage channels including preamplifiers and ADC can be calibrated using a calibrated reference AC voltage source [13]. In addition, the phase performance of the two channels and its dependence on the frequency should be verified and possibly be taken into account with the evaluation processing in the computer. 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.

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D.4 Numerical air flux compensation

The numerical air flux compensation can be done similar to the principle of mutual inductor (see, for instance, [8]).

$$U_{2c}(t) = U_{2m}(t) - \frac{C}{R_n} \cdot \frac{dU_1(t)}{dt} \tag{D.4}$$

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

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

C is the value of compensation factor in Ohm seconds;

U_1 is the voltage drop across the precision resistor R in volts;

R_n is the resistance of the non-inductive precision resistor R in series with the primary winding in ohms.

First, the voltage drop across the precision resistor R, , $U_1(t)$, is differentiated in a way to avoid phase shifts and significant noise amplification injected from the current signal. A possible method can be a five-point or twelve-point differentiation.

Secondly, the compensation can be done as shown in Formula (D.4).

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

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

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Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester

Matériaux magnétiques –
Partie 3: Méthodes de mesure des caractéristiques magnétiques des bandes et tôles magnétiques en acier à l'aide de l'essai sur tôle unique

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MAGNETIC MATERIALS –

Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester

FOREWORD

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IEC 60404-3 has been prepared by IEC technical committee 68: Magnetic alloys and steels. It is an International Standard.

This third edition cancels and replaces the second edition published in 1992, Amendment 1:2002 and Amendment 2:2009. This edition constitutes a technical revision.

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

a) Annex A was revised. The method of determining the yokes' lamination resistance was added to Annex A;
b) Annex B of the consolidated version of 2010 referred to calibration of the SST using the Epstein method. It was cancelled;
c) Annex B (new), Annex C and Annex D were revised, they are for information only;
d) Annex C was modified taking account of the new situation regarding P and R grades;
e) Annex D was amended by addition of Clause D.4 on the numerical air flux compensation.

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

Draft	Report on voting
68/699/CDV	68/710/RVC

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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 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
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MAGNETIC MATERIALS –

Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester

1 Scope

This part of IEC 60404 is applicable to grain-oriented and non-oriented electrical steel strip and sheet for measurement of AC magnetic properties at power frequencies.

The object of this document is to define the general principles and the technical details of the measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester (SST).

The single sheet tester is applicable to test specimens obtained from electrical steel strips and sheets of any grade. The AC magnetic characteristics are determined for sinusoidal induced voltages, for specified peak values of the magnetic polarization, for specific peak values of the magnetic field strength 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 Throughout this document, the quantity "magnetic polarization" is used as defined in IEC 60050-221. In some standards of the IEC 60404 series, the quantity "magnetic flux density" was used.

In order to support the long-term reliability of the performance of this set up and to understand better the relationship between the Epstein method and the SST method, the informative Annexes B and C, respectively, have been included.

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 – Part 221: Magnetic materials and components*

IEC 60404-13, *Magnetic materials – Part 13: Methods of measurement of resistivity, density and stacking factor of electrical steel strip and sheet*

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 https://www.electropedia.org/

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- ISO Online browsing platform: available at https://www.iso.org/obp

4 General principles of AC measurements

4.1 General

Clause 4 specifies the general conditions for the determination of AC magnetic properties of electrical steel strip and sheet at power frequencies by means of a single sheet tester.

4.2 Principle of the single sheet tester method

The test specimen comprises a sample of electrical steel sheet and is placed in the center of two concentric windings:

– an exterior primary winding (magnetizing winding);

– an interior secondary winding (voltage winding).

The flux closure is made by a magnetic circuit consisting of two identical yokes, the cross-section of which is very large compared with that of the test specimen (see Figure 1).

The temperature changes of the specimen shall be kept below a level likely to produce stress in the test specimen due to thermal expansion or contraction.

4.3 Test apparatus

4.3.1 Yokes

Each yoke is in the form of a U made up of insulated sheets of grain-oriented electrical steel. It shall have a low reluctance and a low specific total loss in the low magnetic polarization region below 0,2 T (see Annex A). It shall be manufactured in accordance with the requirements of Annex A.

In order to reduce the effect of eddy currents and give a more homogeneous distribution of the flux over the inside of the yokes, the yokes shall be made of a pair of wound cut C-cores or a glued stack of laminations in which case the corners shall have staggered butt joints (see Figure 1).

The yoke shall have pole faces having a width of 25 mm ± 1 mm.

The two pole faces of each yoke shall be coplanar to within 0,5 mm and the gap between the opposite pole faces of the yokes shall not exceed 0,005 mm at any point. Also, the yokes shall be rigid in order to avoid creating mechanical stresses such as twisting, tensioning and compression in the test specimen.

The height of each yoke shall be between 90 mm and 150 mm. Each yoke shall have a width of 500^{+5}_{-0} mm and an inside length of 450 mm ± 1 mm (see Figure 2).

There shall be a non-conducting, non-magnetic support on which the test specimen is placed, between the vertical limbs of the bottom yokes. This support shall be centered and located in the same plane as the bottom yoke pole faces so that the test specimen is in direct contact with the pole faces without any gap. Care shall be taken that in no case the upper surface of the support is positioned higher than the plane of the pole faces of the bottom yoke.

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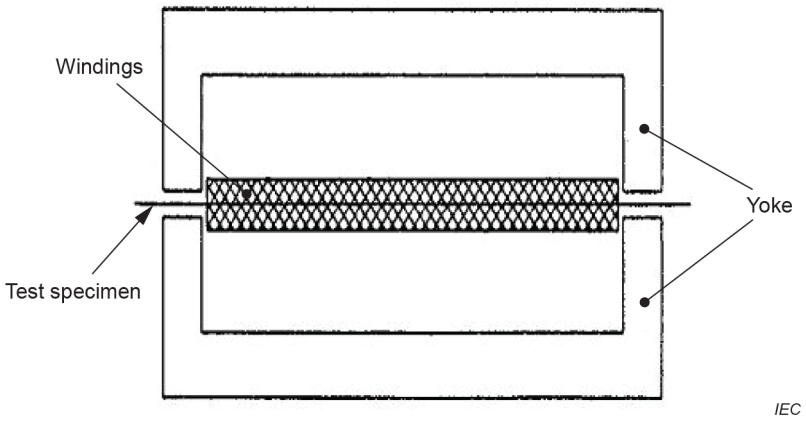
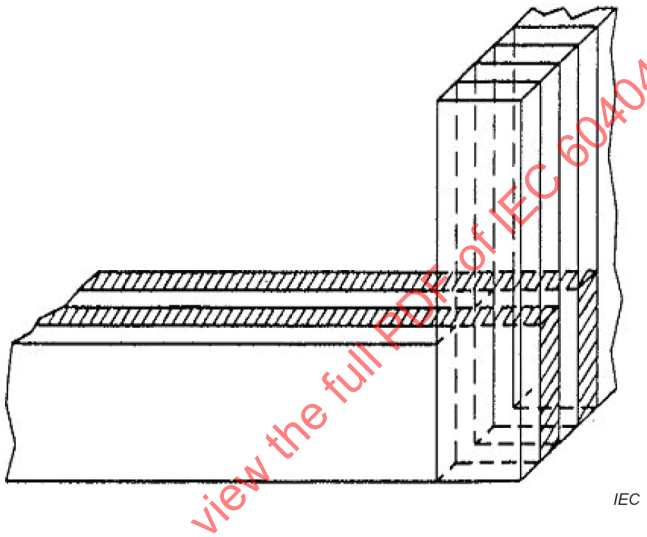


a) Cross-section of the SST



b) Schematic view of the corner of a yoke with stacked lamination

Figure 1 – Schematic diagrammes of the test apparatus

The upper yoke shall be movable upwards to permit insertion of the test specimen. After insertion of the test specimen, the upper yoke shall be lowered to close the magnetic circuit and, simultaneously the pole faces of the bottom and upper yokes shall be aligned accurately. To minimize the effects of pressure on the test specimen, the upper yoke shall be provided with a means of suspension. The suspension of the upper yoke shall allow part of its weight to be counterbalanced so as to give a force on the test specimen of between 100 N and 200 N.

NOTE The square configuration of the yoke has been chosen in order to have only one test specimen for non-oriented material. By rotating the test specimen through 90°, it is possible to determine the characteristics in the rolling direction and perpendicular to the rolling direction.

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Dimensions in millimetres

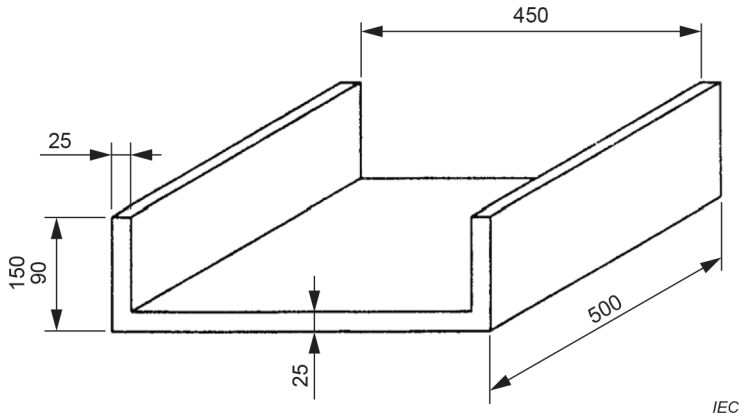

Figure 2 – Yoke dimensions

4.3.2 Windings

The coil system inside the yokes shall have two windings:

– a primary winding, on the outside (magnetizing winding);
– a secondary winding, on the inside (voltage winding);

The primary (outer) and secondary (inner) windings shall be at least 440 mm in length and shall be wound uniformly on a non-conducting, non-magnetic and rectangular former. The dimensions of the former shall be as follows:

– length: 445 mm ± 2 mm;
– internal width: 510 mm ± 1 mm;
– internal height: 5^{0}_{-2} mm;
– height: ≤ 15 mm.

The primary winding can be made up of:

– either five or more coils having identical dimensions and the same number of turns connected in parallel and taking up the whole length (see Figure 3). For example, with five coils, each coil can be made up of 400 turns of copper wire 1 mm in diameter, wound in five layers;
– or a single continuous and uniform winding taking up the whole length. For example, this winding can be made up of 400 turns of copper wire 1 mm in diameter, wound in one layer.

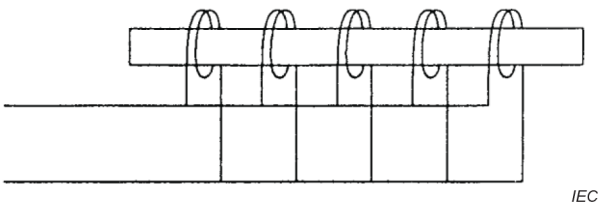

Figure 3 – Diagram of the connections of the five coils of the primary winding

The number of turns on the secondary winding will depend on the characteristics of the measuring instruments. In any case, the determination of the number of turns of the primary and secondary windings shall be made with greatest reliability because a mistake would mean a permanent error.

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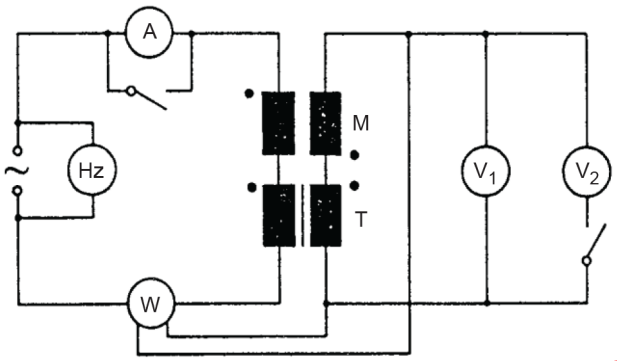
4.4 Air flux compensation

Compensation shall be made for the effect of air flux. This can be achieved, for example, by a mutual inductor M (see Figure 4). The primary winding of the mutual inductor is connected in series with the primary winding of the test apparatus, while the secondary winding of the mutual inductor is connected to the secondary winding of the test apparatus in series opposition.



Key

V_1 is the voltmeter that measures the average rectified voltage;

V_2 is the voltmeter that measures the RMS voltage;

A is the ammeter that measures the RMS value of the primary current;

Hz that measures the frequency;

W that measures the power;

M is the mutual inductor;

T is the test frame.

Figure 4 – Circuit for the determination of the specific total loss

The adjustment of the value of the mutual inductance shall be made so that when passing an alternating current through the primary windings in the absence of the test specimen in the test apparatus, the voltage measured between the non-common terminals of the secondary windings shall be no more than 0,1 % of the voltage appearing across the secondary winding of the test apparatus alone. Thus, the average value of the rectified voltage induced in the combined secondary windings is proportional to the peak value of the magnetic polarization in the test specimen.

NOTE 1 Alternatively, the air flux compensation can be executed by the numerical method (for details, see Annex D, Clause D.4).

NOTE 2 In the rest of this document, the term “compensated secondary voltage” is used to mean “voltage induced in the secondary winding compensated for the effect of air flux”.

4.5 Test specimen

The length of the test specimen shall be not less than 500 mm. Although the part of the test 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 width of the test specimen shall be as large as possible and at its maximum equal to the width of the yokes.

For optimum accuracy, the minimum width shall be not less than 60 % of the width of the yokes.

NOTE 1 Specific restrictions of the dimensions of the test specimens can be defined for special material grades in the respective product standards for magnetic materials.

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NOTE 2 Information about application of the SST to strip samples of 50 mm to 250 mm width: Grain-oriented electrical steel used for distribution transformer (DT) cores is merchandized in the form of slit coils of 50 mm to 250 mm width cut from the as produced steel strips (parent coils) at the different positions across the original strips. The slit coils reflect the considerable variation of the material properties corresponding to the position on the original strip, where they have been cut from. These small strip specimens can be measured using this SST placing them side by side or with distributed gaps in the SST. In order to obtain a relevant measurement result, a minimum of 60 % of the 500 mm wide sample space needs to be filled with strips. The test strip samples can be taken successively from the start or the end of a slit coil. When preparing them taking care would avoid any damage which could influence the test result. Due to the cutting of the sheet into the small strips, the measured loss of narrow strips will be slightly increased compared to the original 500 mm.

The test specimen shall be cut without the formation of excessive burrs or mechanical distortion. The test specimen shall be plane. When a test specimen is cut, the edge of the parent coil is taken as the reference direction. The angle between the direction of rolling and that of cutting shall not exceed:

±1° for grain oriented steel sheet;

±5° for non-oriented steel sheet.

For non-oriented steel sheet, two specimens shall be cut, one parallel to the direction of rolling and the other perpendicular unless the test specimen is square, in which case one test specimen only is necessary.

4.6 Power supply

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

In addition, the waveform of the compensated secondary voltage shall be maintained as sinusoidal as possible. The form factor of the compensated secondary voltage shall be maintained to within ±1 % of 1,111. This can be achieved by various means, for example by using an electronic feedback amplifier or by a computational digital feedback system.

5 Determination of the specific total loss

5.1 Principle of measurement

The test apparatus with the inserted test specimen represents an unloaded transformer the total loss of which is measured by the circuit shown in Figure 4.

5.2 Apparatus

5.2.1 Voltage measurement

5.2.1.1 Average type voltmeter

The average rectified value of the compensated secondary voltage shall be measured by an average type voltmeter. The preferred instrument is a digital voltmeter having an uncertainty of ±0,2 % or better.

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

The load on the secondary circuit shall be as small as possible. Consequently, the internal resistance of the average type voltmeter should be at least 1 000 Ω/V.

NOTE 2 For the application of digital sampling methods, see Annex D.

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5.2.1.2 RMS voltmeter

A voltmeter responsive to RMS values shall be used. The preferred instrument is a digital voltmeter having an uncertainty of ±0,2 % or better.

NOTE For the application of digital sampling methods, see Annex D.

5.2.2 Frequency measurement

A frequency meter having an uncertainty of ±0,1 % or better shall be used.

NOTE For the application of digital sampling methods, see Annex D.

5.2.3 Power measurement

The power shall be measured by a wattmeter having an uncertainty of ±0,5 % or better at the actual power factor and crest factor.

The ohmic resistance of the voltage circuit of the wattmeter shall be at least 100 Ω/V for all ranges. If necessary, the losses in the secondary circuit shall be subtracted from the indicated loss value, see Formula (3) in 5.3.3.1.

The ohmic resistance of the voltage circuit of the wattmeter shall be at least 5 000 times its reactance, unless the wattmeter is compensated for its reactance.

If a current measuring device is included in the circuit, it shall be short-circuited when the secondary voltage is adjusted and the loss is measured.

NOTE For the application of digital sampling methods, see Annex D.

5.3 Measurement procedure of the specific total loss

5.3.1 Preparation of measurement

The length of the test specimen shall be measured with an uncertainty of ±0,1 % or better and its mass determined within ±0,1 %. The test specimen shall be loaded and centred on the longitudinal and transverse axes of the windings, and the partly counterbalanced upper yoke shall be lowered.

Before the measurement, the test specimen shall be demagnetized by slowly decreasing an alternating magnetic field starting from well above the knee of the magnetization curve of the test specimen material.

5.3.2 Adjustment of power supply

The power supply output shall be slowly increased until the average rectified value of the compensated secondary voltage, $\overline{|U_2|}$ has reached the required value. This value is calculated from the desired value of the magnetic polarization by means of:

$$\overline{|U_2|} = 4 f N_2 \frac{R_i}{R_i + R_t} A \hat{J} \tag{1}$$

where

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

f is the frequency, in hertz;

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R_i is the combined resistance of instruments in the secondary circuit, in ohms;

R_t is the series resistance of the secondary windings of the test apparatus and the mutual inductor, in ohms;

N_2 is the number of turns of the secondary winding;

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

$\hat{J}$ is the peak value of the magnetic polarization, in teslas.

The cross-sectional area A of the test specimen is given by the formula:

$$A = \frac{m}{l\,\rho_m} \tag{2}$$

where

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

l is the length of the test specimen, in metres;

ρ_m is the conventional density of the test material, or the value determined in accordance with IEC 60404-13, in kilograms per cubic metre.

5.3.3 Measurements

5.3.3.1 The primary current shall be checked to ensure that the current circuit of the wattmeter is not overloaded. If a current-measuring device is included in the circuit, it shall be short-circuited when the secondary voltage is adjusted and the loss is measured.

After checking that the waveform of the compensated secondary voltage stands within the required tolerances, the wattmeter shall be read. The value of the specific total loss shall then be calculated from the formula:

$$P_s = \left[P\frac{N_1}{N_2} - \frac{(\tilde{U}_2)^2}{R_i} \right] \frac{l}{m l_m} \tag{3}$$

Where P_s

$\tilde{U}_2$ is the RMS value of the compensated secondary voltage, in volts;

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

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

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

l_m is the conventional magnetic path length, in metres (l_m = 0,45 m);

l is the length of the test specimen, in metres;

N_1 is the number of turns of the primary winding;

N_2 is the number of turns of the secondary winding;

R_i is the combined resistance of instruments in the secondary circuit, in ohms.

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NOTE Studies have shown that the inside length between the vertical inner faces of the limbs of the yokes is an appropriate mean value for the effective magnetic path length l_m for various materials under test and polarization values [1][1].

5.3.3.2 In the case of non-oriented electrical steel, for values of the specific total loss specified in the product standards for magnetic materials, the reported value of the specific total loss shall be calculated as the average of the two measurement results obtained for the directions parallel and perpendicular to the direction of rolling. For other purposes, the values of the specific total loss parallel and perpendicular to the direction of rolling shall be reported separately.

5.3.4 Reproducibility of the measurement of the specific total loss

The reproducibility of this method using the test apparatus defined above is characterized by a relative standard deviation of 1 % (for detailed information on the source of this number see [2]) for grain-oriented electrical steel sheet and 2 % for non-oriented electrical steel sheet.

6 Determination of magnetic field strength, primary current and specific apparent power

6.1 General

This Clause 6 describes measuring methods for the determination of the following characteristics:

– peak value of the magnetic polarization $\hat{J}$;
– RMS value of the primary current $\tilde{I}_1$;
– peak value of the magnetic field strength $\hat{H}$;
– specific apparent power S_s.

NOTE For the application of digital sampling methods, see Annex D.

6.2 Principle of measurement

6.2.1 Peak value of the magnetic polarization

The peak value of the magnetic polarization shall be derived from the average rectified value of the compensated secondary voltage measured as described in 5.2.1.1.

6.2.2 RMS value of the primary current

The RMS value of the primary current shall be measured by an RMS ammeter in the circuit of Figure 5.

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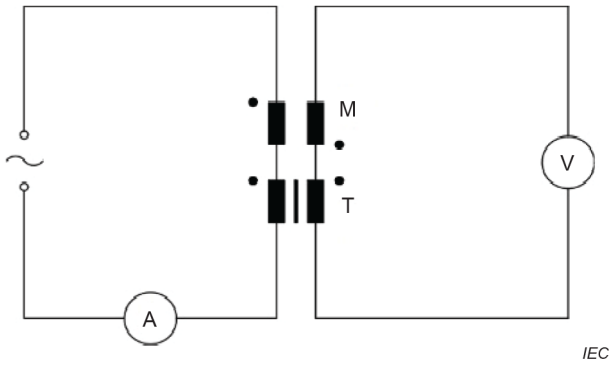
[1] Numbers in square brackets refer to the Bibliography.



Key

V is the voltmeter that measures the average rectified voltage;

A is the ammeter that measures the RMS value of the primary current;

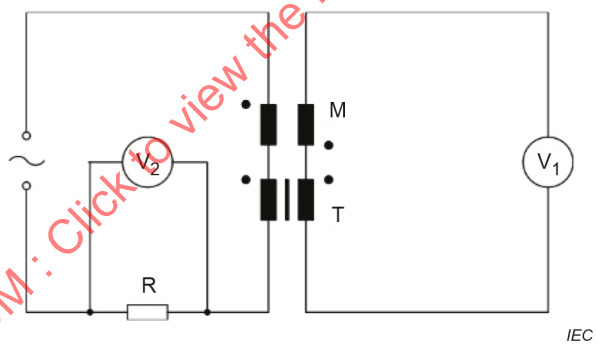
M is the mutual inductor;

T is the test frame.

Figure 5 – Circuit for measuring the RMS value of the primary current

6.2.3 Peak value of the magnetic field strength

The peak value of the magnetic field strength shall be obtained from the peak value $\hat{I}$ of the primary current. This shall be determined by measuring the voltage drop across a known precision resistor R as described in 6.3.5 using an electronic voltmeter of high sensitivity indicating the peak value as shown as V_2 in Figure 6.



Key

V_1 is the voltmeter that measures the average rectified value of the compensated secondary voltage;

V_2 is the voltmeter that measures the peak value (or the RMS value, see 6.3.2) of the voltage drop across the non-inductive precision resistor;

R is the non-inductive precision resistor;

M is the mutual inductor;

T is the test frame.

Figure 6 – Circuit for measuring the peak value of the magnetic field strength

6.3 Apparatus

6.3.1 Average type voltmeter

The average type voltmeter shall be in accordance with 5.2.1.1.

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6.3.2 RMS current measurement

The RMS value of the primary current shall be measured either by means of an RMS ammeter of low impedance of class 0,5 or better (see Figure 5), or by using a precision resistor and an RMS voltmeter described in 5.2.1.2 (see Figure 6, in this case the peak voltmeter is to be replaced by an RMS voltmeter).

6.3.3 Peak current measurement

The measurement of the peak voltage across the resistor R (see Figure 6) shall be achieved either by means of an electronic voltmeter of high sensitivity indicating the peak value, or by means of a calibrated oscilloscope.

A peak voltmeter having an uncertainty of ±0,5 % or better shall be used.

6.3.4 Power supply

The power supply shall be in accordance with 4.6.

6.3.5 Resistor R

The method shown in Figure 6 requires a precision non-inductive resistor R of a value known to within ±0,1 %.

The resistance value of the resistor R shall not exceed 1 Ω in order to minimize the distortion of the magnetizing voltage and, thus, to facilitate the sinusoidal waveform of the induced secondary voltage.

6.4 Measuring procedure

6.4.1 Preparation for measurement

The length of the test specimen shall be measured with an uncertainty of ±0,1 % or better and its mass shall be determined with an uncertainty of ±0,1 % or better. The test specimen shall be loaded and centered on the longitudinal and transverse axes of the windings coil. The partly counterbalanced upper yoke shall then be lowered.

Before the measurement, the test specimen shall be demagnetized by slowly decreasing an alternating magnetic field starting from well above the knee of the magnetization curve of the test specimen material.

6.4.2 Measurement

In practice, single values or groups of peak values of the magnetic polarization $\hat{J}$ and the magnetic field strength ($\hat{H}$ or $\widetilde{H}$) are determined.

If the peak value of the magnetic field strength is specified and the peak value of the magnetic polarization is to be determined, the primary current shall be set to give the relevant magnetic field strength (see below). Then the compensated secondary voltage of the test apparatus shall be read on the average type voltmeter (see 5.2.1.1).

Again, if the peak vale of the magnetic polarization is specified and the peak value of the magnetic field strength is to be determined, the secondary voltage shall be set to its specified value as described in 5.3.2.

For the determination of $\widetilde{H}$, the RMS value of the primary current shall be read on the RMS ammeter according to the circuit of Figure 5 or on the RMS voltmeter according to the circuit of Figure 6.

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For the determination of $\hat{H}$, the peak value of the voltage drop across resistor R shall be read on the peak voltmeter or the calibrated oscilloscope.

6.4.3 Non-oriented material

In the case of non-oriented material, for the peak value of the magnetic polarization $\hat{J}$ at the peak value of the magnetic field strength $\hat{H}$ specified in the product standards for magnetic materials, the reported value of $\hat{J}$ shall be calculated as the average over the two measurement results obtained for the directions parallel and perpendicular to the direction of rolling. For values of $\hat{J}$ for other purposes and for the measurement of the specific apparent power and the RMS value of the primary current, the values obtained for the directions parallel and perpendicular to the direction of rolling shall be reported separately.

6.5 Determination of characteristics

6.5.1 Determination of $\hat{J}$

6.5.1.1 Peak value $\hat{J}$ of the magnetic polarization

The peak value of the magnetic polarization is given by the formula:

$$\hat{J} = \frac{1}{4 f N_2 A} \frac{R_i + R_t}{R_i} \overline{|U_2|} \tag{4}$$

where

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

f is the frequency, in hertz;

N_2 is the number of turns of the secondary winding;

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

R_i is the combined resistance of instruments in the secondary circuit, in ohms;

R_t is the series resistance of the secondary windings of the test apparatus and the mutual inductor, in ohms;

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

6.5.1.2 Reproducibility of $\hat{J}$

The reproducibility of this method using the test apparatus defined above is characterized by a relative standard deviation of 0,25 %.

6.5.2 Determination of $\tilde{H}$

The RMS value of the magnetic field strength shall be calculated from the RMS value of the primary current indicated by the RMS ammeter in the circuit of Figure 5 or by the RMS voltmeter in the circuit of Figure 6 as described in 6.3.2:

$$\tilde{H} = \frac{N_1}{l_m} \tilde{I}_1 \tag{5}$$

where

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

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N_1 is the number of turns of the primary winding;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,45 m);

$\tilde{I}_1$ is the RMS value of primary current, in amperes.

NOTE After several groups of corresponding values of $\hat{J}$ and $\tilde{H}$ have been determined, the magnetization curve of $\hat{J}$ against $\tilde{H}$ can be drawn.

6.5.3 Determination of $\hat{H}$

The peak value of the magnetic field strength shall be calculated from the peak value of the primary current $\hat{U}_m / R_n$ indicated by the peak voltmeter in the circuit of Figure 6 as described in 6.3.3:

$$\hat{H} = \frac{N_1}{R_n l_m} \hat{U}_m \tag{6}$$

where

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

R_n is the resistance value of the non-inductive precision resistor R in Figure 6, in ohms;

$\hat{U}_m$ is the peak voltage drop across resistor R, in volts.

NOTE 1 The amplitude permeability is expressed as:

$$\mu_a = \frac{\hat{J}}{\mu_o \hat{H}} + 1$$

NOTE 2 After several groups of corresponding values of $\hat{J}$ and $\hat{H}$ have been determined, the magnetization curve of $\hat{J}$ against $\hat{H}$ can be drawn.

6.5.4 Determination of S_s

The apparent power is given by:

$$S = \tilde{I}_1 \cdot \tilde{U}_2 \cdot \frac{N_1}{N_2} = \tilde{I}_1 \cdot 1{,}111 \cdot \overline{|U_2|} \cdot \frac{N_1}{N_2} \tag{7}$$

where

S is the apparent power, in voltamperes;

$\tilde{U}_2$ is the RMS value of secondary voltage of the single sheet tester, in volts.

NOTE The relation $\tilde{U}_2 = 1{,}111 \cdot \overline{|U_2|}$ is valid only for sinusoidal voltage.

Division of this quantity by the effective mass of the test specimen $m_a = \frac{l_m}{l} m$ gives the specific apparent power:

$$S_s = \frac{S}{m_a} = \frac{\tilde{I} \cdot 1{,}111 \cdot \overline{|U_2|} l N_1}{m l_m N_2} \tag{8}$$

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where

S_s is the specific apparent power, in voltamperes per kilogram;

l is the length of the test specimen, in metres;

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

m_a is the effective mass of the test specimen; in kilograms

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

N_1 is the number of turns of the primary winding;

N_2 is the number of turns of the secondary winding;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,45 m);

$\tilde{I}_1$ is the RMS value of primary current, in amperes.

6.5.5 Reproducibility of the measurement of the specific apparent power

The reproducibility of this method using the test apparatus defined above is characterized by a relative standard deviation of 3 % or less.

7 Test report

The test report shall include the following, as applicable:

a) the type and identity of test specimen;
b) the density of material (conventional or as determined in accordance with IEC 60404-13)
c) the length and width of test specimen;
d) the ambient temperature of measurement;
e) the measurement frequency;
f) the peak values of the magnetic polarization or the magnetic field strength;
g) the results of the measurements.

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Annex A
(normative)

Requirements concerning the manufacture of yokes

It is important to ensure that the power loss dissipated by the yokes is stable and small compared with the total power loss dissipated by the specimen. A power loss of 1 mW/kg at a magnetic flux density of 40 mT or of 0,1 mW/kg at 10 mT are typical, measured at a frequency of 50 Hz (see Figure B.1 and Table B.1). Ways in which the loss can become high are short circuits between laminations in the yokes and uneven distribution of the magnetic flux inside the yokes. For the measurement of the power loss dissipated by the yokes, a primary and a secondary winding wound on the yokes or on appropriate formers shall be used. Four sets of outer primary and inner secondary windings shall be arranged symmetrically on the four vertical limbs of the yokes and switched in series connection. The number of turns depends on the configuration of the measurement instruments. As a typical case. the number of 25 turns for each sub-winding was found to work properly. The windings shall be disconnected when not used for the yokes' loss measurement.

During the manufacture of the yokes with stacked lamination, a stress relief annealing of the cut strips is required. After bonding the material to build the yokes (which shall be done without application of high pressure), the pole faces shall be machined. Parallelism shall be proven with an appropriate gauge, and the uniformity of the air gap checked using engineer's blue. Further grinding in stages using carborundum and diamond paste will probably be necessary until a uniform distribution of the engineer's blue indicates a sufficiently homogeneous air gap. The grinding can be carried out by putting the upper yoke in the normal position of use on top of the bottom yoke and moving it to and fro through a small distance.

With wound cut C-cores corresponding measures shall be taken so that equivalent performance characteristics are achieved.

The process of grinding causes the metal to flow between laminations and produces short circuits. It is important to remove this flowed metal by a careful acid etching process using a non-oxidizing acid (e.g. hydrochloric acid). This consists in rubbing the pole faces with an acid-soaked cloth until the flowed layer is removed. It is important to carefully neutralize and wash away the acid remaining on the pole faces and between the laminations.

It is helpful to measure the yoke's loss before and after grinding and etching to verify that the loss has been reduced by this treatment.

A thorough check of the inter-laminar insulation of the yokes with stacked lamination shall be made after pole face etching and cleaning. The electrical resistance of the laminations of the upper and the bottom yokes shall be measured separately. The resistance of all the 10 sections, 5 cm long each, along the pole faces of the yokes shall be measured using a contact pattern strip (see, for instance, Figure 3 in [2]) and an ohmmeter with an uncertainty of 1 % or better. For monitoring that the transition resistance at each contact is negligible, the resistance measurements shall be expanded over all groups of two neighbouring 5-cm sections, i.e. over all section pairs 10 cm in length. The resistance value of the 10-cm section pairs shall agree within 5 % with the sum of the two resistance values measured separately over the respective two 5-cm sections. For proper contact, it is recommended to apply a thin strip of slightly compressible non-conductive material under the contact strip (correspondingly, on top of the contact strip when measuring the bottom yoke). The measurements can be made at the air gap of the front side while the rear side air gap shall be equipped with a strip of isolating material. For the measurements, the upper yoke shall be set down on the lower yoke.

The resistance value of each 5-cm section of both yokes shall be 10 Ω at least. This minimum value was found with the high quality yokes in the series studied in the exercise shown in Figure 4 of IEC TR 62981:2017 [2]. The resistance measured between the outermost laminations of the yokes (over the full length of 50 cm) is then 100 Ω at least. For the case of wound cut C-core yokes it is estimated that, correspondingly, the resistance measured between

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the outermost laminations shall be again not less than 100 Ω:Thus, the outermost eddy current path encloses the same magnetic flux in both cases of lamination type.

The inspection of the yokes shall be documented by the manufacturer of the measurement set-up in a detailed record.

NOTE Details of how to measure the resistivity of the yokes' 5-cm sections are given in IEC TR 62981 [2].

Before use, the yokes shall be carefully demagnetized from a magnetic flux density well above the knee of the magnetization curve of the yoke material. The windings for the yokes' loss measurement can be used for the demagnetizing. The power loss dissipated by the yokes at the magnetic polarization which would occur inside the yokes during use shall be measured and recorded by the manufacturer of the SST set-up in the course of the mandatory quality check of the yokes before delivery.

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Annex B
(informative)

Check and verification of reliable performance of the SST set-up by the use of reference samples and impact of the loss dissipated in the yokes

The continuous checking of the performance reliability of a SST set-up is recommended to be properly managed by the use of reference samples. This is particularly relevant with test specimens of high permeability materials which are most sensitive with regard to performance alterations of the set-up. It is recommendable that the laboratory has a set of reference samples to their disposal which represents the properties of the materials the set-up is mostly used for.

It is also recommended to provide reference samples with magnetic properties certificated by standards laboratories that have taken part to the latest IEC round robin tests [2] and are able to trace the sample's magnetic characteristics to the results of that RRT, or by laboratories having a specific accreditation.

If conspicuous deviation from expected values appear which also are reproduced when applying a reference sample of known magnetic characteristics, a check of the electrical measuring part of the set-up should additionally be made using appropriate means, for instance a calibrated double signal generator delivering certified electrical power values in the relevant measurement range.

The systematic error of the SST method is formed by the magnetic loss dissipated in the flux closing yokes (see 4.3.1). Its relative contribution to the measured loss value depends on the flux density, grade and thickness of the specimen under test and amounts to about 2 % for high quality electrical steel sheets at 1,7 Tesla. To benchmark this relative to Epstein frames' performance, it is noted that, roughly, the SST measures the specific total loss too high by 2 % and the Epstein frame too low by 4 % (see also [2]).

Studies on the performance of three standard yoke systems (Figure 1), two with a stacked lamination (SST1 and SST3) and one with wound C-cut core lamination (SST2) were made at the German standard institute PTB [3] in 1990. The measurement results are shown in Figure B.1 supplemented by Epstein measurements in the upper region made at IENGF by G. Bertotti [4]. They present the loss dissipated by various yokes systems and corresponding Epstein measurements in the low flux density region which reflect the situation in the yokes under test conditions.

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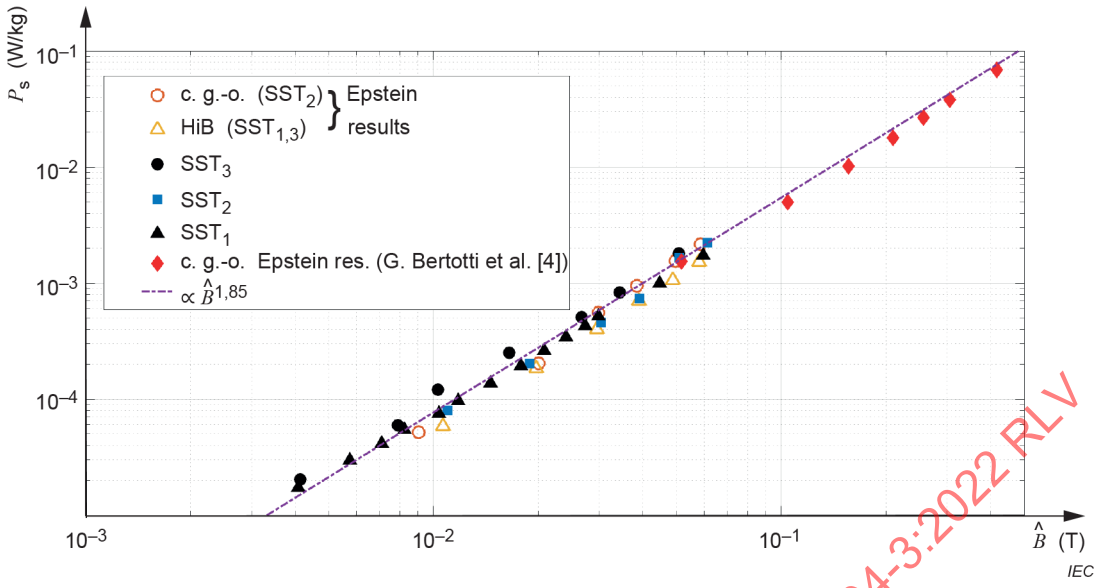

Figure B.1 – Specific total loss vs. peak flux density (after J. Sievert [3] and G. Bertotti [4]); straight line: $P_S \propto B^{1.85}$ approximation (after C. Ragusa).

It can be seen that the three yoke systems, including the wound C-cut core type, show agreement within a certain statistical dispersion. The Epstein results of corresponding S-type (c.g.-o.) and P-type (HiB) grain-oriented material are located - also G. Bertotti's results in the upper part - a bit below the yokes' results. Generally it appears that, in the very low flux density region, the performance of different yokes systems is equalized because the magnetizing processes are dominated by domain wall bowing without excess loss production as also can be concluded from the zero Barkhausen noise in that region. These phenomena could also explain the amazing agreement of performance of a variety of 10 yokes within the IEC RRT (2013/2014) [2]. Moreover, in line with this picture are the findings reported by SST manufacturers, that strong loss variation between yokes made of different materials in the 1.0 T to 1.7 T region are not reflected in the 10 mT region, i.e. the variations in high flux region appear to be not really relevant to the yokes' quality under the relevant test conditions.

The measured loss characteristic of yoke loss values for the relevant flux densities allow to determine the relative contribution of the yokes, p_Y:

$$p_Y = \frac{P_Y}{P_{Sp}} \tag{B.1}$$

where

P_Y is the power loss dissipated by the yokes under test conditions, in watts;

P_{Sp} is the total loss of the model specimen at 1,7 T, in watts.

Table B.1 shows 5 examples of grades and their relevant quantities under test conditions at 1,7 T using the data given in Figure B.1. They demonstrate the contribution of the yokes to the measured value of the total specific loss.

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Table B.1 – Loss dissipated by the yokes of a standard SST, determined from the loss curves measured on 3 yoke pairs as shown in Figure B.1, and relevant quantities including the relative yokes' contribution, p_Y; exemplified using 5 standard grades

Steel name (examples of grades)	Nominal thickness of specimen, d	Nominal Loss, P_{sp} of modelling specimen at 1,7 T	Flux density $\hat{f}_y$ of yokes at 1,7 T of specimen	Specific total loss in yokes at 1,7 T of specimen	Total loss in yokes, P_Y at 1,7 T in the specimen	Relative contribution of the yokes $p_Y = P_Y/P_{Sp}$
	mm	W	T	W/kg	W	(x100), %
M130-30S5	0,30	0,658	0,010 2	0,000 085	0,011	1,7
M100-27P5	0,27	0,456	0,009 2	0,000 068	0,008 8	1,9
M90-23P5	0,23	0,349	0,007 8	0,000 050	0,006 5	1,9
M80-23P5	0,23	0,310	0,007 8	0,000 050	0,006 5	2,1
M70-20P5	0,20	0,236	0,006 8	0,000 040	0,005 2	2,2

The subtraction of the yokes' power loss will effectuate that the result approaches the physical true value of loss. However, it should be taken into account that the method is afflicted with considerable indeterminacy due to the imperfectness of the model used at the air gap region and the difficult measurement condition in the low flux region. The uncertainty of this correction procedure is estimated to amount to 10 % to 20 % of the correction (error of error).

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Annex C
(informative)

Epstein to SST relationship for grain-oriented steel sheet

This Annex C does not form part of the requirements of this document. It is included for information for those who wish to convert SST values into Epstein values and vice versa. It should be noted that the determination of the Epstein/SST ratio usually shows a considerable dispersion from sample-to-sample pair even for identical grades. In fact, this was the reason for defining an SST method independent from the Epstein method (changing SST(1982) to SST (1992)).

This Annex C describes the conversion of SST to Epstein values and vice versa in general, i.e. where only one of the two methods of measurements has been performed. The general validity of the presented relationships is restricted because it is subject to larger uncertainty of the conversion due to the statistical scatter through the varying internal stress of the individual sheet samples and, even more relevant, through the considerable scattering of the Epstein strip samples preparation with GO materials. The dispersion of the presented relative SST- Epstein difference results δP amounts to about ±2 % (for the whole range of $\hat{J}$) for the specific total loss, P_s, from about ±2 % (at $\hat{J}$ = 1,3 T) to ±10 % (at 1,7 T) for the field strength quantities, H, and from about ±5 % (at 1,3 T) to ±20 % (at 1,7 T) for the specific apparent power ([5] and [6]). The dispersion (uncertainty) values are also a rough estimation only because the scatter is not normally distributed. Thus, to avoid misunderstanding, it was abstained from indicating error bars in the diagrams.

The relationships were achieved on the basis of Epstein and SST measurements on about 740 samples of the most significant S-type grain-oriented grades, supplied by eight different manufacturers and taken from different production runs. For further details see [5] and [6]. This study did include very few of high permeability (P) grades which did not show specific performance.

This informative Annex C is not applicable to the new group of R-type domain-refined (RD) materials for which, after intense discussions on this issue, a specific SST to Epstein conversion factor F_c = 0,925 at $\hat{J}$ = 1,7 T was introduced [7]. Transformer designers report that they also apply the findings presented in this Annex C to the design of transformers using non domain-refined P-type materials.

The relationship between Epstein and SST results can be described by the relative differences (in %) δP (for the specific total loss, P) and δHS (for the magnetic field strength, H and the specific apparent power, S). The conversion of Epstein results, $P_{s,EPS}$, H_{EPS} and $S_{s,EPS}$, to SST results, $P_{s,SST}$, H_{SST} and $S_{s,SST}$, can be carried out using the following formulas:

$$P_{s,SST} = P_{s,EPS} \times (1 + \delta P/100) \quad \text{(C.1)}$$

$$H_{SST} = H_{EPS} \times (1 + \delta HS/100) \quad \text{(C.2)}$$

$$S_{s,SST} = S_{s,EPS} \times (1 + \delta HS/100) \quad \text{(C.3)}$$

Correspondingly, the conversion in the reverse direction can be carried out using the inverse of Formulae C.1, C.2 and C.3 resulting in Formulae C.4, C,5 and C.6:

$$P_{s,EPS} = P_{s,SST} / (1 + \delta P/100) \quad \text{(C.4)}$$

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$$H_{EPS} = H_{SST} / (1 + \delta HS/100) \quad (C.5)$$

$$S_{s,EPS} = S_{s,SST} / (1 + \delta HS/100) \quad (C.6)$$

NOTE The relation between the Conversion Factor F_C and δP is given by the formula $F_C = 1/(1+\delta P/100)$.

The averaged relative differences as determined from the experiments (see reference [5] and [6]) are shown as rhombus symbols in the diagrams of Figure C.1 for δP and Figure C.2 for δHS. The values for $\hat{J}$, 1,0 T to 1,2 T, were obtained by extrapolation from the experimental data. The two diagrams also comprise the curve fits to the experimental data (continuous lines). The relationships representing the curve fits are as follows:

$$\delta P = 1{,}46 + 0{,}242\ \hat{J}^5 \quad (C.7)$$

$$\delta HS = 6{,}0 + 0{,}103\ \hat{J}^{10} \quad (C.8)$$

The relative differences as obtained from Formulae (C.7) and (C.8) and the related conversion factor are presented in Table C.1. As remarked above, the values aim first and foremost at S-type grain-oriented grades, however, the application to non-domain refined P-grade materials has also been reported.

Table C.1 – SST-Epstein relative differences δP and δHS and the conversion factor F_C for conventional grain-oriented material in the polarization range 1,0 T to 1,8 T

$\hat{J}$ T	δP %	δHS %	$F_C = 1/(1+\delta P/100)$
1,0	1,7	6,1	0,983
1,1	1,8	6,3	0,982
1,2	2,1	6,6	0,979
1,3	2,4	7,4	0,977
1,4	2,8	9,0	0,973
1,5	3,3	12	0,968
1,6	4,0	17	0,962
1,7	5,0	27	0,952
1,8	6,0	43	0,943

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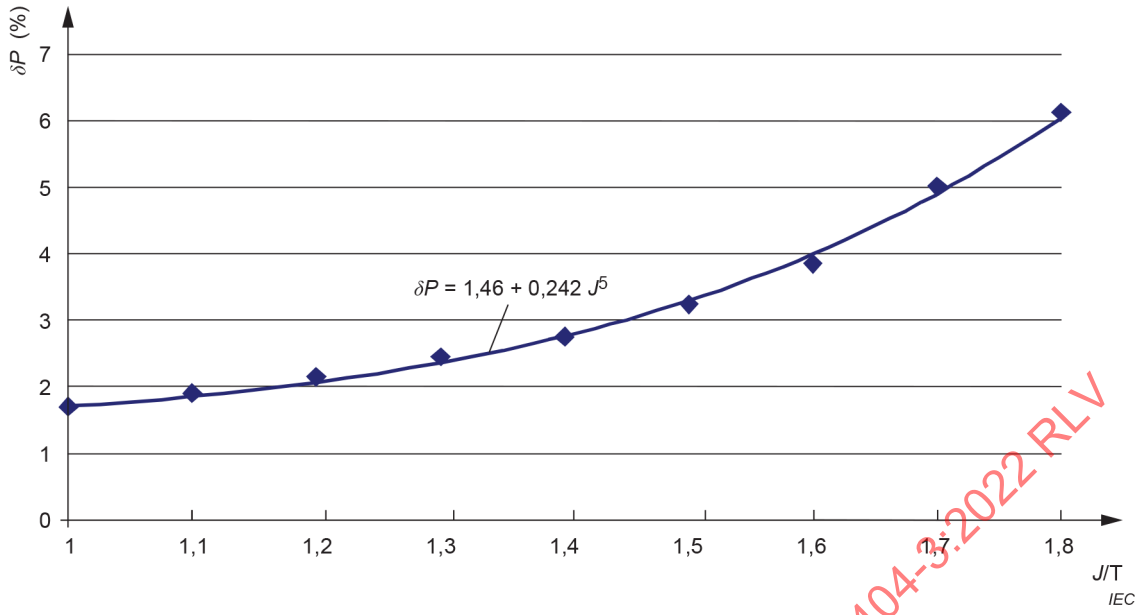
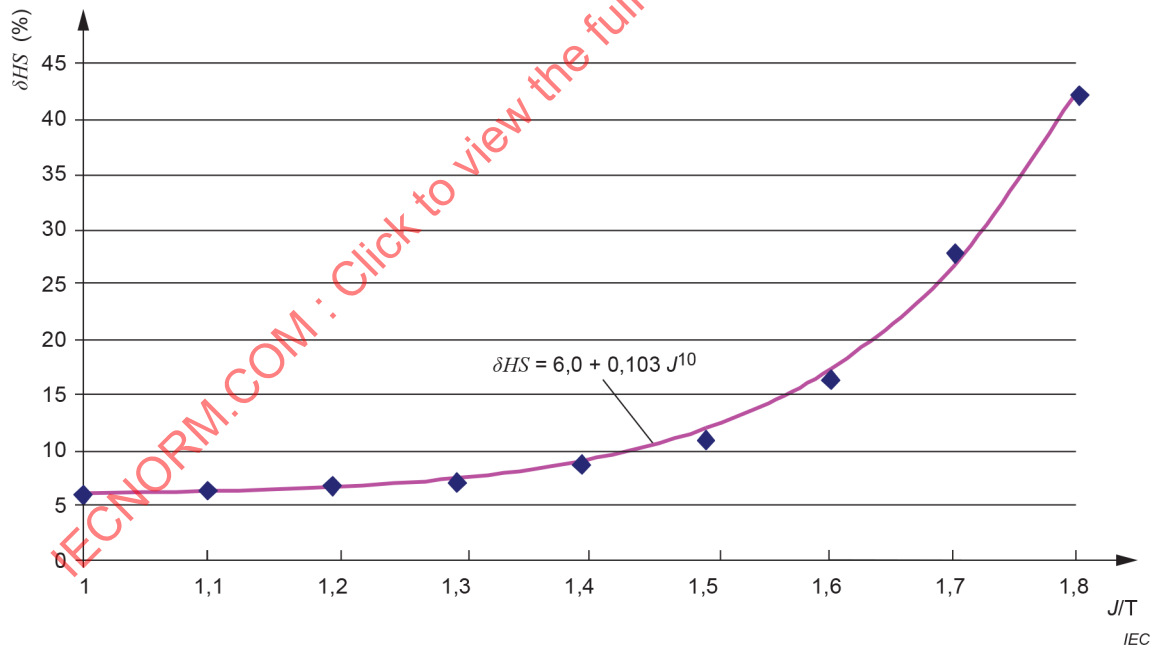


Key

Rhombus symbols = experimental data (values at 1,0 T to 1,2 T were extrapolated using the measured values)

Continuous line = curve fit to the experimental data according to Formula (C.7)

Figure C.1 – SST-Epstein relative difference δP for conventional grain-oriented material versus magnetic polarization $\hat{J}$



Key

Rhombus symbols = experimental data (values at 1,0 T to 1,2 T were extrapolated using the measured values).

Continuous line = curve fit to the experimental data according to formula (C.8).

Figure C.2 – SST-Epstein relative difference δHS for conventional grain-oriented material versus magnetic polarization $\hat{J}$

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Annex D
(informative)

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

D.1 General

The digital sampling method is an advanced technique that is becoming almost exclusively applied to the electrical part of the measurement procedure of this document. It is characterized by the digitalization of the compensated secondary voltage, $U_2(t)$, the voltage drop across the non-inductive precision resistor in series with the primary winding (see Figures 4 and 6), $U_1(t)$, and the evaluation of the 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_{1j} respectively, are sampled and held simultaneously from the time-dependent voltage functions during the narrow and equidistant time periods 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 specimen 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.

The digital sampling method may be applied to the measurement procedures which are described in the main part of this document. The block diagram in Figure 4 applies equally to the analogue methods and the digital sampling method, the digital sampling method allows all functions of the measurement equipment in Figure 4, Figure 5 and Figure 6 to be realized by a combined system of a data acquisition equipment and software. The control of the sinusoidal waveform of the 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 D and are not treated here. More information can be found in [8] and [9].

This Annex D is helpful in understanding the impact of the digital sampling method on the precision achievable by the methods of this document. This is particularly important because ADC circuits, transient recorders and supporting software are easily available thus encouraging one to build one's own wattmeter. The digital sampling method can offer low uncertainty, but it leads to large errors if improperly used.

D.2 Technical details and requirements

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

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

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 seconds.

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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 [10] and the sampling frequency, f_s, should be greater than twice the higher order harmonic of the input signal (Nyquist-Shannon condition [10]).

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:

$$\hat{J} = \frac{1}{4fN_2A}\frac{1}{T}\int_{t=0}^{T}\left|U_2(t)\right|dt \cong \frac{1}{4f_sN_2A}\sum_{j=0}^{n-1}\left|u_{2j}\right| \tag{D.2}$$

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

$$P_s = \frac{1}{l_mA\rho_m}\left(\frac{N_1}{R_nN_2}\frac{1}{T}\int_{t=0}^{T}U_1(t)U_2(t)dt - \frac{\tilde{U}_2^{\,2}}{R_i}\right) \cong \frac{1}{l_mA\rho_m}\left(\frac{N_1}{R_nN_2}\frac{1}{n}\sum_{j=0}^{n}u_{1j}u_{2j} - \frac{1}{R_i}\frac{1}{n}\sum_{j=0}^{n-1}u_{2j}^{\,2}\right) \tag{D.3}$$

where

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

P_s is the specific total loss of the specimen, in watts 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_1 is the number of turns of the primary 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;

R_n is the resistance of the non-inductive precision resistor R in series with the primary winding (see Figure 6), in ohms;

U_1 is the voltage drop across the non-inductive precision resistor R, in volts;

U_2 is the secondary voltage, in volts;

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

j is the index of instantaneous values;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,45 m);

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

R_i is the combined resistance of the instruments in the secondary circuit, in ohms;

$\tilde{U}_2$ is the RMS value of the voltage induced in the secondary winding, in volts.

---

[2] The peak value of the magnetic field strength and the apparent power can be calculated correspondingly by using $\hat{H} = \frac{N_1}{R_n l_m}\hat{U}_1$ and $S_s \cong \frac{N_1}{l_m R_n N_2 A\rho_m}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}u_{1j}^{\,2}}\sqrt{\frac{1}{n}\sum_{j=0}^{n-1}u_{2j}^{\,2}}$

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The pairs of values, u_{2j} and u_{1j}, 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, $U_1(t)$ 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 [11]. 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 must 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 (for instance at 400 Hz which is within the scope of this document). The use of a low-pass anti-aliasing filter [10] 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 [11,12] have shown that below a 12-bit resolution, the digitalization 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 phase shift should be small enough so that the power measurement uncertainty specified in this document, namely 0,5 %, is not exceeded. The consideration of the phase shift is more relevant the lower the power factor $\cos(\varphi)$ becomes (φ being the phase shift between the fundamental components of the two voltage signals). For this reason, the concept of a single channel with multiplexer leading to different sampling times for the instantaneous values of the two voltages is not to be recommended.

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.

D.3 Calibration aspects

The verification of the repeatability and reproducibility requirements of this document make careful calibration of the measurement equipment necessary. The two voltage channels including preamplifiers and ADC can be calibrated using a calibrated reference AC voltage source [13]. In addition, the phase performance of the two channels and its dependence on the frequency should be verified and possibly be taken into account with the evaluation processing in the computer. 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.

D.4 Numerical air flux compensation

The numerical air flux compensation can be done similar to the principle of mutual inductor (see, for instance, [8]).

$$U_{2c}(t) = U_{2m}(t) - \frac{C}{R_n} \cdot \frac{dU_1(t)}{dt} \tag{D.4}$$

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

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

C is the value of compensation factor in Ohm seconds;

U_1 is the voltage drop across the precision resistor R in volts;

R_n is the resistance of the non-inductive precision resistor R in series with the primary winding in ohms.

First, the voltage drop across the precision resistor R, , $U_1(t)$, is differentiated in a way to avoid phase shifts and significant noise amplification injected from the current signal. A possible method can be a five-point or twelve-point differentiation.

Secondly, the compensation can be done as shown in Formula (D.4).

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

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

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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MATÉRIAUX MAGNÉTIQUES –

Partie 3: Méthodes de mesure des caractéristiques magnétiques des bandes et tôles magnétiques en acier à l'aide de l'essai sur tôle unique

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Cette troisième édition annule et remplace la première édition parue en 1992, l'Amendement 1:2002 et l'Amendement 2:2009. Cette édition constitue une révision technique.

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

a) l'Annexe A a été révisée. La méthode de détermination de la résistance des bandes des culasses a été ajoutée à l'Annexe A;
b) l'Annexe B de l'édition consolidée de 2010 faisait référence à l'étalonnage du SST à l'aide de la méthode Epstein. Elle a été annulée;

c) l'Annexe B (nouvelle), l'Annexe C et l'Annexe D ont été révisées et sont seulement informatives;

d) l'Annexe C a été modifiée compte tenu de la nouvelle situation concernant les qualités P et R;

e) l'Annexe D a été amendée par ajout de l'Article D.4 relatif à la compensation numérique du flux d'air.

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

Projet	Rapport de vote
68/699/CDV	68/710/RVC

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

La langue employée pour l'élaboration de cette Norme internationale est l'anglais.

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MATÉRIAUX MAGNÉTIQUES –

Partie 3: Méthodes de mesure des caractéristiques magnétiques des bandes et tôles magnétiques en acier à l'aide de l'essai sur tôle unique

1 Domaine d'application

La présente partie de l'IEC 60404 s'applique aux bandes et tôles magnétiques en acier à grains orientés et à grains non orientés pour le mesurage des caractéristiques magnétiques en courant alternatif aux fréquences industrielles.

Le présent document a pour objet de définir les principes généraux et les détails techniques pour le mesurage des caractéristiques magnétiques des bandes et tôles magnétiques en acier à l'aide de l'essai sur tôle unique (SST, *Single Sheet Tester*).

L'essai sur tôle unique s'applique aux éprouvettes prélevées à partir de bandes et de tôles magnétiques en acier de toute qualité. Les caractéristiques magnétiques en courant alternatif sont déterminées pour des tensions induites sinusoïdales, pour les valeurs de crête spécifiées de la polarisation magnétique, pour les valeurs de crête spécifiques de l'intensité du champ magnétique et pour une fréquence spécifiée.

Les mesurages sont effectués à la température ambiante de (23 ± 5) °C sur des éprouvettes qui ont été au préalable désaimantées.

NOTE Dans le présent document, la grandeur "polarisation magnétique" est utilisée conformément à la définition de l'IEC 60050-221. Dans certaines normes de la série IEC 60404, la grandeur "induction magnétique" a été utilisée.

Afin de soutenir la fiabilité à long terme des performances de cette configuration et de mieux comprendre la relation entre la méthode Epstein et la méthode SST, les annexes informatives B et C, ont été respectivement, ajoutées.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils 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 – Partie 221: Matériaux et composants magnétiques*

IEC 60404-13, *Matériaux magnétiques – Partie 13: Méthodes de mesure de la résistivité, de la masse volumique et du facteur de foisonnement des bandes et tôles en acier électrique*

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:

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

4 Principes généraux des mesurages en courant alternatif

4.1 Généralités

L'Article 4 spécifie les conditions générales relatives à la détermination des caractéristiques magnétiques en courant alternatif des bandes et tôles magnétiques en acier aux fréquences industrielles, à l'aide de l'essai sur tôle unique.

4.2 Principe de la méthode d'essai sur tôle unique

L'éprouvette, constituée d'un échantillon de tôle magnétique en acier, est placée au centre de deux enroulements concentriques:

– un enroulement primaire extérieur (enroulement de magnétisation);

– un enroulement secondaire intérieur (enroulement de tension).

La fermeture du flux est assurée par un circuit magnétique constitué de deux culasses identiques dont la section est très importante par rapport à celle de l'éprouvette (voir Figure 1).

Les variations de température de l'éprouvette doivent être maintenues à un niveau inférieur à celui susceptible de produire une tension dans l'éprouvette par dilatation ou contraction thermique.

4.3 Appareillage d'essai

4.3.1 Culasses

Chaque culasse en forme de U est composée de tôles isolées en acier magnétique à grains orientés. Elle doit présenter une faible réluctance et de faibles pertes totales spécifiques dans la région à faible polarisation magnétique, au-dessous de 0,2 T (voir Annexe A). Elle doit être fabriquée selon les exigences de l'Annexe A.

Afin de réduire l'effet des courants de Foucault et d'obtenir une répartition plus homogène du flux à l'intérieur de la culasse, celle-ci doit être constituée d'une paire de culasses en C coupées et bobinées, ou d'un assemblage collé de bandes, auquel cas les coins doivent être à joints croisés (voir Figure 1).

Les faces polaires de la culasse doivent avoir une largeur de 25 mm ± 1 mm.

Les deux faces polaires de chaque culasse doivent être coplanaires à 0,5 mm près, et l'entrefer entre les faces polaires opposées des culasses ne doit dépasser 0,005 mm en aucun point. En outre, les culasses doivent être rigides afin d'éviter toute contrainte mécanique telle qu'une torsion, une tension ou une compression appliquée à l'éprouvette.

La hauteur de chaque culasse doit être comprise entre 90 mm et 150 mm. Chaque culasse doit avoir une largeur de 500^{+5}_{-0} mm et une longueur interne de 450 mm ± 1 mm (voir Figure 2).

L'éprouvette doit être placée sur un support en matériau isolant et non magnétique, entre les branches verticales des culasses inférieures. Ce support doit être centré et placé dans le même plan que les faces polaires de la culasse inférieure, afin que l'éprouvette soit en contact direct avec les faces polaires sans entrefer. Des précautions doivent être prises afin que la surface supérieure du support ne soit positionnée en aucun cas plus haut que le plan des faces polaires de la culasse inférieure.

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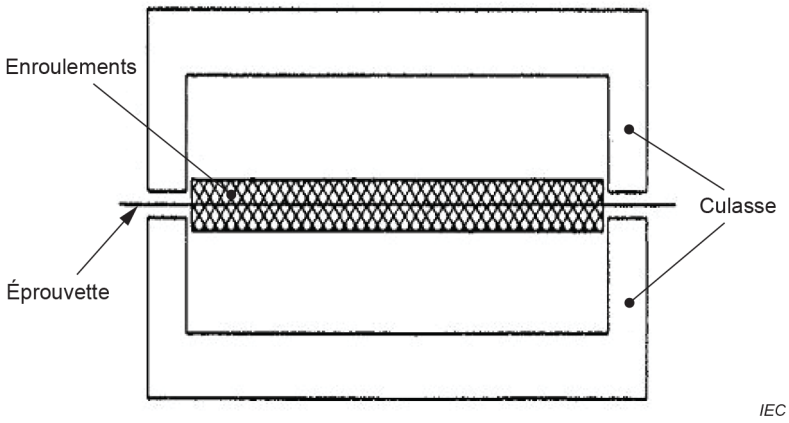
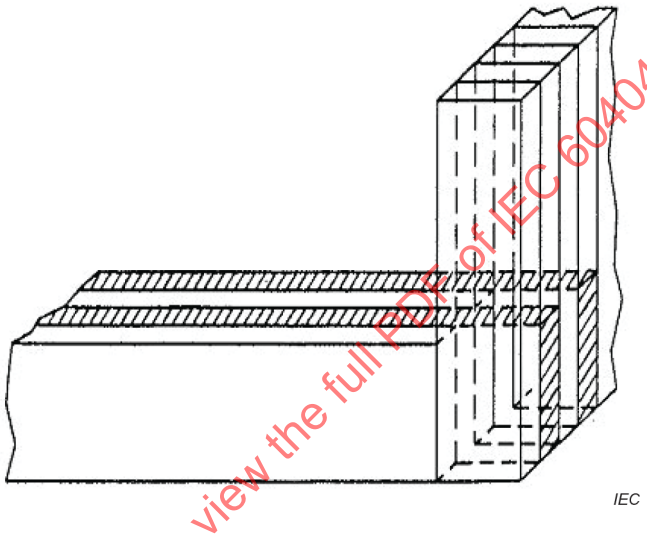


a) Section du SST



b) Vue schématique du coin d'une culasse à bandes assemblées

Figure 1 – Schémas de l'appareillage d'essai

La culasse supérieure doit être mobile pour permettre la mise en place de l'éprouvette. Après la mise en place de l'éprouvette, la culasse supérieure doit être abaissée pour fermer le circuit magnétique et, simultanément, les faces polaires des culasses inférieure et supérieure doivent parfaitement s'aligner. Afin de réduire le plus possible les effets de pression sur l'éprouvette, la culasse supérieure doit être équipée d'un système de suspension. La suspension de la culasse supérieure doit permettre de contrebalancer une partie de son poids afin d'obtenir une force sur l'éprouvette comprise entre 100 N et 200 N.

NOTE La configuration carrée de la culasse a été retenue afin de permettre l'utilisation d'une seule éprouvette dans le cas des matériaux à grains non orientés. Par rotation de 90° de l'éprouvette, il est possible de déterminer les caractéristiques dans la direction de laminage et perpendiculairement à celle-ci.

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Dimensions en millimètres

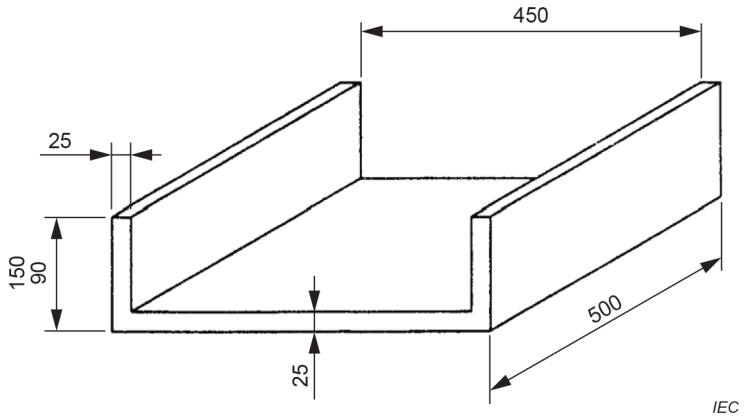

Figure 2 – Dimensions de la culasse

4.3.2 Enroulements

Le système de bobine qui se trouve à l'intérieur des culasses doit comporter deux enroulements:

– un enroulement primaire, à l'extérieur (enroulement de magnétisation);
– un enroulement secondaire, à l'intérieur (enroulement de tension).

Les enroulements primaire (extérieur) et secondaire (intérieur) doivent avoir une longueur d'au moins 440 mm et doivent être enroulés uniformément sur un support en matériau isolant, non magnétique et de forme rectangulaire. Les dimensions du support doivent être les suivantes:

– longueur: 445 mm ± 2 mm;
– largeur interne: 510 mm ± 1 mm;
– hauteur interne: $5^{\ 0}_{-2}$ mm;
– hauteur: ≤ 15 mm.

L'enroulement primaire peut être constitué:

– soit de cinq bobines ou plus de mêmes dimensions et de même nombre de spires, réparties sur toute la longueur et reliées en parallèle (voir Figure 3). Par exemple, avec cinq bobines, chaque bobine peut comporter 400 spires de fil de cuivre de 1 mm de diamètre, bobinées en cinq couches;
– soit d'un enroulement unique continu et uniformément réparti sur toute la longueur. Par exemple, cet enroulement peut comporter 400 spires de fil de cuivre de 1 mm de diamètre, bobinées en une seule couche.

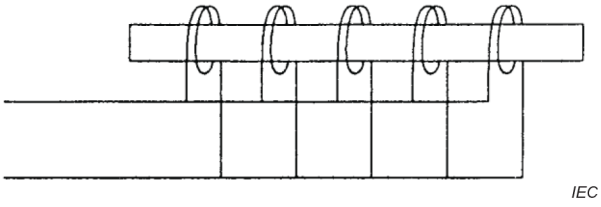

Figure 3 – Schéma de branchement des cinq bobines de l'enroulement primaire

Le nombre de spires de l'enroulement secondaire dépend des caractéristiques des instruments de mesure. Dans tous les cas, la détermination du nombre de spires des enroulements primaire et secondaire doit être effectuée avec la plus grande fiabilité, car une erreur entraînerait une erreur permanente.

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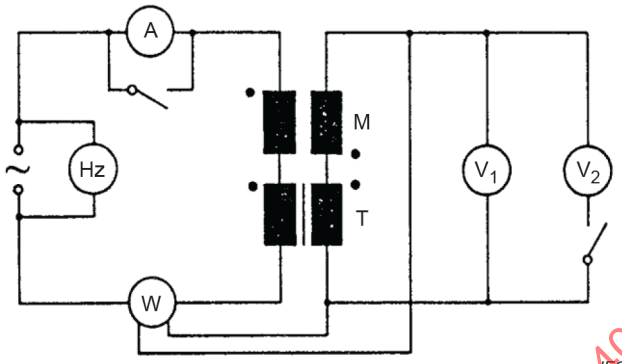
4.4 Compensation du flux d'air

L'effet de flux d'air doit être compensé. Cela peut être obtenu, par exemple, à l'aide d'une inductance mutuelle M (voir Figure 4). L'enroulement primaire de l'inductance mutuelle est connecté en série avec l'enroulement primaire de l'appareillage d'essai, tandis que l'enroulement secondaire de l'inductance mutuelle est connecté en opposition avec l'enroulement secondaire de l'appareillage d'essai.



Légende

V_1 est le voltmètre qui mesure la tension moyenne redressée

V_2 est le voltmètre qui mesure la tension en valeur efficace

A est l'ampèremètre qui mesure la valeur efficace du courant primaire

Hz mesure la fréquence

W mesure la puissance

M est l'inductance mutuelle

T est le cadre d'essai

Figure 4 – Circuit pour la détermination des pertes totales spécifiques

La valeur de l'inductance mutuelle doit être réglée de façon telle qu'en l'absence d'éprouvette dans l'appareillage d'essai, lorsqu'un courant alternatif circule dans les enroulements primaires, la tension mesurée entre les bornes non reliées entre elles des enroulements secondaires ne doit pas être supérieure à 0,1 % de la tension observée dans l'enroulement secondaire de l'appareillage d'essai seul. Ainsi, la valeur moyenne de la tension redressée induite dans les enroulements secondaires combinés est proportionnelle à la valeur de crête de la polarisation magnétique dans l'éprouvette.

NOTE 1 En variante, la compensation du flux d'air peut être obtenue par la méthode numérique (pour plus d'informations, voir Annexe D, Article D.4).

NOTE 2 Dans la suite du présent document, le terme "tension secondaire compensée" signifie "tension induite dans l'enroulement secondaire compensé pour l'effet de flux d'air".

4.5 Eprouvette

La longueur de l'éprouvette doit être d'au moins 500 mm. Même si la partie de l'éprouvette située en dehors des faces polaires n'a pas grande influence sur la mesure, cette partie ne doit pas être plus longue que nécessaire pour faciliter la mise en place et le retrait de l'éprouvette.

La largeur de l'éprouvette doit être aussi importante que possible et au maximum égale à la largeur des culasses.

Pour obtenir l'exactitude maximale, la largeur minimale ne doit pas être inférieure à 60 % de la largeur des culasses.

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NOTE 1 Des restrictions spécifiques relatives aux dimensions des éprouvettes peuvent être définies pour des qualités de matériaux particulières dans les normes de produits respectives des matériaux magnétiques.

NOTE 2 Informations concernant l'application du SST aux échantillons de bande de 50 mm à 250 mm de largeur: l'acier magnétique à grains orientés utilisé pour les noyaux des transformateurs de distribution est commercialisé sous forme de bobines refendues de 50 mm à 250 mm de largeur, découpées dans des bandes en acier brutes (bobines mères), en différentes positions sur les bandes d'origine. Les bobines refendues reflètent la variation considérable des caractéristiques du matériau en fonction de la position sur la bande d'origine dans laquelle elles ont été découpées. Ces petites éprouvettes peuvent être mesurées à l'aide de ce SST en les plaçant côte à côte ou à espaces réguliers dans le dispositif d'essai. Afin d'obtenir une mesure pertinente, il est nécessaire de remplir de bandes au moins 60 % de l'espace d'échantillonnage de 500 mm de largeur. Les échantillons de bandes d'essai peuvent être prélevés successivement au début ou à la fin d'une bobine refendue. Lors de leur préparation, prendre des précautions pour éviter tout dommage susceptible d'influencer le résultat de l'essai. En raison de la découpe de la tôle en bandes de faibles dimensions, les pertes mesurées des bandes étroites sont légèrement supérieures par rapport à celles de la tôle d'origine de 500 mm.

Les éprouvettes doivent être découpées sans formation de bavures excessives ou de distorsions mécaniques. L'éprouvette doit être plane. Lors du découpage, la rive de la bobine mère est prise comme direction de référence. L'angle entre la direction de laminage et celle de découpage ne doit pas dépasser:

±1° pour les tôles en acier à grains orientés;

±5° pour les tôles en acier à grains non orientés.

Pour les tôles en acier à grains non orientés, deux éprouvettes doivent être découpées, l'une parallèlement à la direction de laminage, l'autre perpendiculairement, sauf si l'éprouvette est carrée, auquel cas seule une éprouvette est nécessaire.

4.6 Source d'alimentation

La source d'alimentation doit avoir une faible impédance interne et une stabilité élevée en tension et en fréquence. Pendant les mesurages, la tension et la fréquence doivent être maintenues constantes à ±0,2 %.

En outre, la forme d'onde de la tension secondaire compensée doit être maintenue aussi sinusoïdale que possible. Le facteur de forme de la tension secondaire compensée doit être maintenu à 1,111 ± 1 %. Cela peut être réalisé de différentes manières, par exemple à l'aide d'une amplification électronique asservie ou d'un système numérique de rétroaction par calcul.

5 Détermination des pertes totales spécifiques

5.1 Principe de mesure

L'appareillage d'essai avec l'éprouvette mise en place constitue un transformateur à vide dont les pertes totales sont mesurées selon le circuit représenté à la Figure 4.

5.2 Appareillage

5.2.1 Mesurage de la tension

5.2.1.1 Voltmètre de valeur moyenne

La valeur moyenne redressée de la tension secondaire compensée doit être mesurée à l'aide d'un voltmètre de valeur moyenne. L'instrument privilégié est un voltmètre numérique avec une incertitude de ±0,2 % ou mieux.

NOTE 1 Des instruments de ce type sont généralement gradués en valeur moyenne redressée multipliée par 1,111.

La charge du circuit secondaire doit être aussi faible que possible. Par conséquent, il convient que la résistance interne du voltmètre de valeur moyenne soit au moins égale à 1 000 Ω/V.

NOTE 2 Pour l'application de méthodes d'échantillonnage numérique, voir Annexe D.

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5.2.1.2 Voltmètre de valeur efficace

Un voltmètre de valeur efficace doit être utilisé. L'instrument privilégié est un voltmètre numérique avec une incertitude de ±0,2 % ou mieux.

NOTE Pour l'application de méthodes d'échantillonnage numérique, voir Annexe D.

5.2.2 Mesurage de la fréquence

Un fréquencemètre avec une incertitude de ±0,1 % ou mieux doit être utilisé.

NOTE Pour l'application de méthodes d'échantillonnage numérique, voir Annexe D.

5.2.3 Mesurage de la puissance

La puissance doit être mesurée à l'aide d'un wattmètre avec une incertitude de ±0,5 % ou mieux pour la valeur réelle du facteur de puissance et du facteur de crête.

La résistance ohmique du circuit de tension du wattmètre doit être d'au moins 100 Ω/V pour toutes les plages. Si nécessaire, les pertes dans le circuit secondaire doivent être retranchées des pertes indiquées; voir Formule (3) en 5.3.3.1.

La résistance ohmique du circuit de tension du wattmètre doit être au moins égale à 5 000 fois sa réactance, à moins que le wattmètre ne soit compensé pour celle-ci.

Si un dispositif de mesure du courant est inclus dans le circuit, il doit être court-circuité lors de l'ajustement de la tension secondaire ainsi que lors du mesurage des pertes.

NOTE Pour l'application de méthodes d'échantillonnage numérique, voir Annexe D.

5.3 Mode opératoire pour le mesurage des pertes totales spécifiques

5.3.1 Préparation du mesurage

La longueur de l'éprouvette doit être mesurée avec une incertitude de ±0,1 % ou mieux et sa masse déterminée à ±0,1 % près. L'éprouvette doit ensuite être mise en place et centrée sur les axes longitudinal et transversal des enroulements, et la culasse supérieure, partiellement contrebalancée, doit être abaissée.

Avant le mesurage, l'éprouvette doit être désaimantée par une lente diminution d'un champ magnétique alternatif à partir d'une valeur nettement supérieure au coude de la courbe de magnétisation du matériau de l'éprouvette.

5.3.2 Réglage de la source d'alimentation

La puissance d'alimentation doit être progressivement augmentée, jusqu'à ce que la valeur moyenne redressée de la tension secondaire compensée, $\overline{|U_2|}$, atteigne la valeur exigée. Cette valeur est calculée à partir de la valeur souhaitée de la polarisation magnétique au moyen de la formule:

$$\overline{|U_2|} = 4 f N_2 \frac{R_i}{R_i + R_t} A\tilde{J} \quad (1)$$

où

$\overline{|U_2|}$ est la valeur moyenne de la tension secondaire redressée, en volts;

f est la fréquence, en hertz;

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R_i est la résistance combinée des instruments dans le circuit secondaire, en ohms;

R_t est la résistance-série des enroulements secondaires de l'appareillage d'essai et de l'inductance mutuelle, en ohms;

N_2 est le nombre de spires de l'enroulement secondaire;

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

$\hat{J}$ est la valeur de crête de la polarisation magnétique, en teslas.

La section A de l'éprouvette est donnée par la formule:

$$A = \frac{m}{l\,\rho_{\mathrm{m}}} \tag{2}$$

où

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

l est la longueur de l'éprouvette, en mètres;

ρ_{m} est la masse volumique conventionnelle du matériau à l'essai, ou la valeur déterminée selon l'IEC 60404-13, en kilogrammes par mètre cube.

5.3.3 Mesurages

5.3.3.1 Le courant primaire doit être vérifié afin de s'assurer que le circuit courant du wattmètre n'est pas surchargé. Si un dispositif de mesure du courant est inclus dans le circuit, il doit être court-circuité lors de l'ajustement de la tension secondaire ainsi que lors du mesurage des pertes.

Après avoir vérifié que la forme d'onde de la tension secondaire compensée se situe dans les limites de tolérance exigées, la valeur du wattmètre doit être lue. La valeur des pertes totales spécifiques doit alors être calculée d'après la formule:

$$P_{\mathrm{s}} = \left[P\frac{N_1}{N_2} - \frac{\left(\tilde{U}_2\right)^2}{R_i} \right] \frac{l}{m l_m} \tag{3}$$

où

$\tilde{U}_2$ est la valeur efficace de la tension secondaire compensée, en volts;

P_{s} représente les pertes totales spécifiques de l'éprouvette, en watts par kilogramme;

P est la puissance mesurée par le wattmètre, en watts;

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

l_{m} est la longueur conventionnelle du circuit magnétique, en mètres (l_{m} = 0,45 m);

l est la longueur de l'éprouvette, en mètres;

N_1 est le nombre de spires de l'enroulement primaire;

N_2 est le nombre de spires de l'enroulement secondaire;

R_i est la résistance combinée des instruments dans le circuit secondaire, en ohms.

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