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INTERNATIONAL STANDARD

Magnetic materials –
Part 10: Methods of measurement of magnetic properties of electrical steel strip and sheet at medium frequencies

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MAGNETIC MATERIALS –

Part 10: Methods of measurement of magnetic properties of electrical steel strip and sheet at medium frequencies

FOREWORD

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International Standard IEC 60404-10 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

This second edition cancels and replaces the first edition published in 1988. This edition constitutes a technical revision.

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

a) adaption to modern measurement and evaluation methods, in particular the introduction of the widely spread digital sampling method for the acquisition and evaluation of the measured data;
b) introduction of formal changes which adapt this standard to other standards of the 60404 series;
c) revision of the problem of the air flux compensation taking account of the condition of the higher frequencies;

d) revision of the capacitive coupling of mutual inductor windings together with the consideration of the alternative method of numerical air flux compensation.

The text of this standard is based on the following documents:

CDV	Report of voting
68/523/CDV	68/556/RVC

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

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

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

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

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- withdrawn,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

A bilingual version of this publication may be issued at a later date.

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

INTRODUCTION

Besides the fact that the first edition of this part of IEC 60404 is more than 25 years old, the main purpose of this revision is to adapt it to modern measurement and evaluation methods, in particular to introduce the widely spread digital sampling method for the acquisition and evaluation of the measured data.

In addition, the problem of the air flux compensation had to be re-considered under the condition of the elevated frequencies. Capacitive coupling of mutual inductor windings require observance of significant phase shift influence and suggest consideration of the alternative method of numerical air flux compensation. An increase of the frequency range to 20 kHz was discussed by TC 68 since some manufacturers of electrical steel include this range in their catalogues. However, TC 68 decided to keep the frequency range to that defined in IEC 60404-10:1988: 400 Hz to 10 kHz.

MAGNETIC MATERIALS –

Part 10: Methods of measurement of magnetic properties of electrical steel strip and sheet at medium frequencies

1 Scope

This part of IEC 60404 is applicable to grain-oriented and non-oriented electrical steel strip and sheet for measurements of a.c. magnetic properties in the frequency range 400 Hz to 10 000 Hz.

The object of this document is to define the general principles and the technical details of the measurement of magnetic properties of electrical steel strip and sheet by means of an Epstein frame.

The Epstein frame 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 magnetic polarization and for a specified frequency.

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

NOTE Throughout this document the term "magnetic polarization" is used as defined in IEC 60050-221. In some standards of the IEC 60404 series, the term "magnetic flux density" was used.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism*

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

IEC 60404-8 (all parts), *Magnetic materials – Part 8: Specifications for individual materials*

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

3 Terms and definitions

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

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

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

4 General principle of a.c. measurements

4.1 General

Clause 4 specifies the general conditions for the determination of a.c.magnetic properties of electrical steel strip and sheet by means of the 25 cm Epstein frame.

4.2 Principle of the 25 cm Epstein frame method

The 25 cm Epstein frame, which comprises a primary winding, a secondary winding and the specimen to be tested as a core, forms an unloaded transformer whose characteristics are measured by the method described in the following subclauses 4.3 to 4.10.

At the higher end of the frequency range, a specially constructed Epstein frame (see Annex A) may be required in which the interwinding capacitances are low, so that the capacitive part of the impedance has a negligible impact on the loss results. The material of the winding formers supporting the windings has a low dielectric loss.

A separate measuring system (for example a commercially available digital bridge capable of measuring resistance, capacitance and inductance) is required to determine the inter-winding capacitance of the Epstein frame.

4.3 Test specimen

The strips to be tested are assembled in a square, having double-overlapped corner joints (see Figure 1) thus forming four limbs of equal length and equal cross-sectional area.

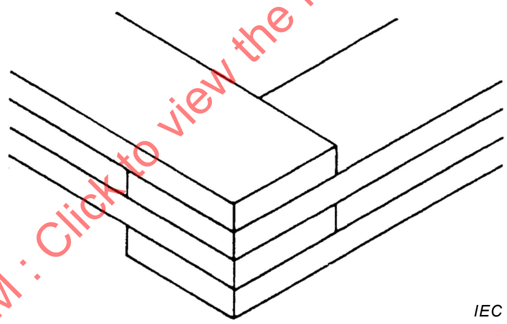


Figure 1 – Double-lapped joints

The strips shall be sampled in accordance with the appropriate product standard in the IEC 60404-8 series.

They shall be cut by a method which will produce substantially burr-free edges and, if so specified, heat treated in accordance with the corresponding product standard. They shall have the following dimensions:

– width b = 30 mm ± 0,2 mm;

– length 280 mm ≤ l ≤ 320 mm.

The length of the strips shall be equal within a tolerance of ± 0,5 mm.

When the strips are cut parallel or normal to the direction of rolling, the edge of the parent sheet shall be taken as the reference direction.

The following tolerances shall apply for the angle between the specified and actual direction of cutting:

– ± 1° for grain-oriented steel sheet;
– ± 5° for non-oriented steel sheet.

Only flat strips shall be used. Measurements shall be made without additional insulation.

The number of strips comprising the test specimen shall be not less than twelve and shall be a multiple of four. A force of (1 ± 0,1) N shall be applied to each corner, normal to the plane of the overlapping strips.

4.4 The 25 cm Epstein frame

The 25 cm Epstein frame (hereinafter referred to as the Epstein frame) shall consist of four solenoids into which the test specimen strips are inserted in such a manner that a closed magnetic circuit is formed (see Figure 2).

Dimensions in millimetres

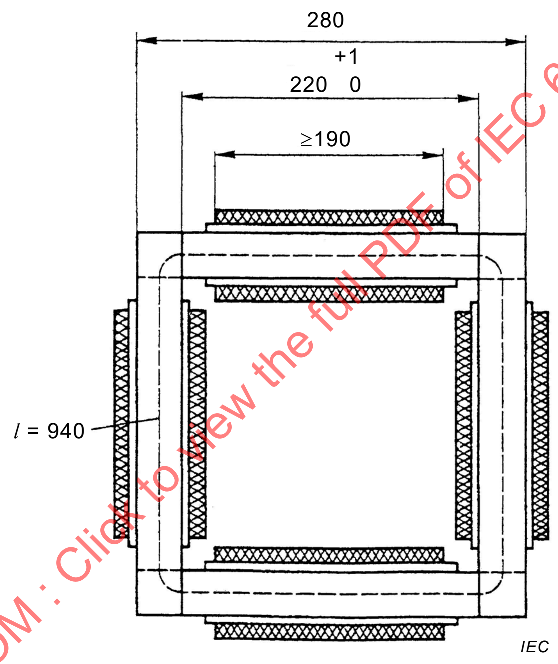


Figure 2 – The 25 cm Epstein frame

If measurements are to be made under the conditions specified in 4.5, a mutual inductor for air flux compensation may be provided.

The winding formers supporting the windings shall be made of hard insulating material of low dielectric loss, such as polystyrene. They have a rectangular cross-section with 32 mm inner width. A height of approximately 5 mm is recommended.

The solenoids shall be fixed to an insulating and non-magnetic base in such a way to form a square (see Figure 2). The length of the sides of the square formed by the internal edges of the strips of the test specimen shall be 220 $^{+1}_{0}$ mm (see Figure 2).

In order to avoid undue wear of the winding formers and especially of their inner surfaces, winding formers of larger cross-section can be used into which replaceable liners of appropriate dimensions may be inserted.

Each of the four solenoids shall have two windings:

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

The windings shall be distributed uniformly over a minimum length of 190 mm, each solenoid having one quarter of the total number of turns.

The individual primary windings of the four solenoids shall be connected in series, and the individual secondary windings shall be connected in a similar fashion.

At the higher end of the frequency range, the loss contribution due to the capacitance between the primary and secondary windings and also the self-capacitance of the secondary winding could be significant. The windings shall be spaced to minimize this loss.

The capacitance between the windings and the self-capacitance of the secondary winding shall be measured. If necessary, a correction shall be applied for the loss introduced.

The number of turns of primary and secondary windings shall be chosen to suit the particular conditions of the power supply, measuring equipment and frequency.

A total number of 200 turns for each of the primary and secondary windings is recommended and is commonly used for tests in the frequency range 400 Hz to 10 000 Hz.

The impedance of the magnetizing windings shall be sufficiently small to avoid waveform distortion and minimize internal voltage drops.

The effective magnetic path length, l_m, of the magnetic circuit shall be conventionally assumed to be equal to 0,94 m.

The active mass, m_a, i.e. the magnetically active mass of the test specimen, is given by:

$$m_a = \frac{l_m}{4l} m \quad (1)$$

where:

m_a is the magnetically active mass of test specimen, in kilograms;

m is the mass of test specimen, in kilograms;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,94 m);

l is the length of a test specimen strip, in metres.

4.5 Air flux compensation

A compensation for air flux shall be made for magnetic field strengths greater than or equal to 1 000 A/m. At the lower end of the frequency range (less than or equal to 1 000 Hz) a mutual inductor may be used to compensate for the air flux.

The primary winding of the mutual inductor shall be connected in series with the primary winding of the Epstein frame, and the secondary winding of the mutual inductor shall be connected to the secondary winding of the Epstein frame in series opposition (see Figure 3).

An adjustment of the value of the mutual inductance shall be made so that, when passing an alternating current through the combined primary windings in the absence of the specimen in the apparatus, the voltage measured between the non-common terminals of the combined 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 rectified value of the voltage induced in the combined secondary windings is proportional to the peak value of the magnetic polarization in the test specimen.

At the higher end of the frequency range, coupling through interwinding capacitances of the mutual inductor can lead to a significant phase shift of the secondary induced voltage followed by a relevant error in the measurement of the magnetic loss value. It has to be ensured that the mutual inductance does not lead to a significant phase shift of the secondary induced voltage. Appropriate design of the secondary winding of the mutual inductor, i.e. larger distances between the windings, can avoid the phase shift. If, at the higher end of the frequency range, a relevant phase shift cannot be avoided in this way, the mutual inductor shall be removed from the measurement circuit and numerical air flux compensation shall be applied (see Clause B.4).

4.6 Power supply

The power supply shall have a low internal impedance and a high stability of voltage and frequency. During the measurement, the voltage and frequency variations shall not exceed ± 0,2 % of the required value.

For the determination of the specific total loss, the specific apparent power and r.m.s. value of the magnetic field strength, the form factor of the secondary induced voltage shall be 1,111 within ± 1 %.

NOTE This is possible in several ways; for example by using an electrically controlled power supply or a negative feedback power amplifier.

The form factor of the secondary induced voltage is the ratio of its r.m.s. value to its average rectified value. Two voltmeters, one responsive to r.m.s. values and the other responsive to average rectified values shall be used to determine the form factor.

When a negative feedback amplifier is used for the supply, it may be necessary to observe the waveform of the secondary induced voltage on an oscilloscope to ensure that the correct waveform of the fundamental frequency is being produced.

4.7 Voltage measurement

4.7.1 General

The secondary induced voltage shall be measured by means of appropriate voltmeters having an input impedance greater than or equal to 1 000 Ω/V.

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

4.7.2 Average type voltmeter

A voltmeter responsive to average rectified values having an accuracy of ± 0,5 % or better shall be used.

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

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

NOTE 2 The preferred instrument is a digital voltmeter.

4.7.3 RMS voltmeter

A voltmeter responsive to r.m.s. values having an accuracy of ± 0,5 % or better shall be used.

NOTE The preferred instrument is a digital voltmeter.

4.8 Current measurement

The magnetizing current shall be measured by either:

– an ammeter having an accuracy ± 0,5 % or better of low impedance;

or

– measuring the voltage drop across a non-inductive precision resistor connected in series with the primary winding. The combined uncertainties of the resistor and the voltmeter shall not exceed 1 %.

The current measuring device shall be short-circuited when the secondary induced voltage has been adjusted and the loss is being measured.

NOTE 1 The preferred instrument is a digital ammeter or a digital voltmeter.

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

4.9 Frequency measurement

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

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

4.10 Power measurement

The power shall be measured by a wattmeter having an accuracy of ± 0,5 % or better at the frequency, power factor, and crest factor to be used. Readings in the first quarter of the scale shall be avoided as far as possible.

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

The 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.

Moreover, 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, to avoid necessary corrections of phase angle.

5 Procedure for the determination of the specific total loss

5.1 General

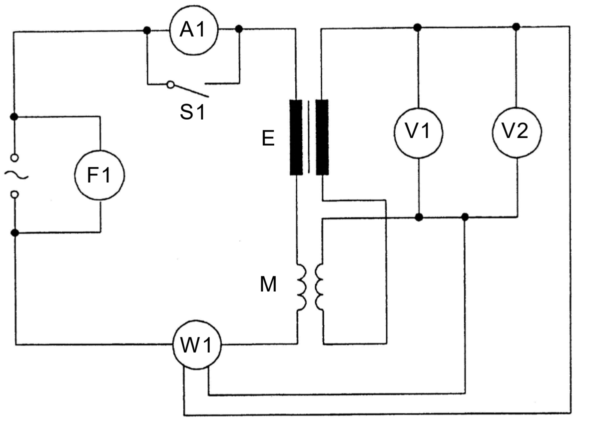
Clause 5 describes the wattmeter method for the determination of the specific total loss of electrical steel strip and sheet at frequencies in the range 400 Hz to 10 000 Hz.

The specific total loss is determined, according to this method, for specified peak values of magnetic polarization and for a specified frequency.

In order to obtain comparable results, test values shall be referred to magnetic polarization of sinusoidal waveform.

5.2 Preparation for measurement

The Epstein frame and measuring equipment shall be connected as shown in Figure 3.



Components

V1 average type voltmeter

V2 r.m.s. voltmeter

A1 current measuring device

F1 frequency meter

W1 wattmeter

M mutual inductor

E Epstein frame

S1 switch

NOTE The circuit diagram of Figure 3 illustrates the principle of the wattmeter method. It also sets out the fundamentals of the digital Wattmeter method where the instrumental functions are realized partly through the evaluating software.

Figure 3 – Circuit for the wattmeter method

The test specimen shall be weighed and its mass determined within ± 0,1 %. After weighing, the strips shall be loaded into the solenoids of the Epstein frame forming double-overlapping corner joints. In the case of strips which are cut half in the direction of rolling and half normal to that direction, care shall be taken that all the strips cut in the direction of rolling are placed in two opposite solenoids of the frame and that those cut normal to that direction are placed in the two other opposite solenoids. The joints shall form a minimum gap between the strips. The strips shall be positioned so as to conform with the requirements of 4.4. The number of strips shall be the same in each solenoid.

Before measurement, the test specimen shall be demagnetized by a decreasing alternating magnetic field of an initial level higher than used in previous measurements.

5.3 Adjustment of power supply

In order to achieve the specified peak value of the polarisation, $\hat{J}$, the power supply output shall be adjusted so that the average rectified value of the secondary induced voltage is:

$$\overline{|U_2|} = 4\,f N_2 \left(\frac{R_i}{R_i + R_t} \right) A \hat{J} \qquad (2)$$

where:

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

f is the frequency, in hertz;

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

R_t is the series resistance of the combined secondary windings, in ohms;

N_2 is the number of turns of the secondary winding of the Epstein frame;

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

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

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

$$A = \frac{m}{4l\rho_m} \tag{3}$$

where:

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

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

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

5.4 Measurements of power

The ammeter in the primary circuit shall be observed to ensure that the current circuit of the wattmeter is not overloaded. Then the ammeter shall be short-circuited and the secondary induced voltage readjusted. After checking the waveform of the secondary induced voltage in compliance with 4.6, the wattmeter shall be read.

In order to avoid undue heating of the test specimen and to facilitate reproducibility, measurements should be made as quickly as possible after energizing the Epstein frame. The specimen should be allowed to cool between readings.

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

5.5 Determination of the specific total loss

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

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

Thus, the total loss, P of the test specimen shall be calculated from the formula:

$$P_c = \frac{N_1}{N_2} \cdot P_m - \frac{\left(1{,}111 \cdot \overline{|U_2|}\right)^2}{R_i} \tag{4}$$

where:

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

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

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 equivalent resistance of the instruments in the secondary circuit, in ohms;

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

The specific total losses, P_s shall be obtained by dividing P_c by the magnetically active mass of the test specimen (see 4.4).

$$P_s = \frac{P_c}{m_a} = \frac{P_c \cdot 4l}{m \cdot l_m} \tag{5}$$

where:

P_s is the specific total losses of test specimen, in watts per kilogram (corrected if necessary for flux waveform distortion according to 4.4);

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

m_a is the magnetically active mass of test specimen, in kilograms;

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

l_m is the conventional effective magnetic path length, in metres (l_m = 0,94 m).

5.6 Reproducibility of the specific total loss measurement

The reproducibility of the results obtained from this method is characterized by a relative standard deviation in the range between 2 % and 5 %, the value of this standard deviation depending on the frequency and the magnetic polarization which are used.

6 Procedure for the determination of the peak value of magnetic polarization, r.m.s. value of magnetic field strength, peak value of magnetic field strength and specific apparent power

6.1 General

Clause 6 describes measuring methods for the determination of the following quantities:

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

– r.m.s. value of magnetic field strength $\tilde{H}$;

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

– specific apparent power S_s.

The quantities are determined, according to these methods, for specified peak values of magnetic polarization and for a specified frequency.

6.2 Test specimen

The test specimen shall comply with 4.3.

6.3 Principle of measurement

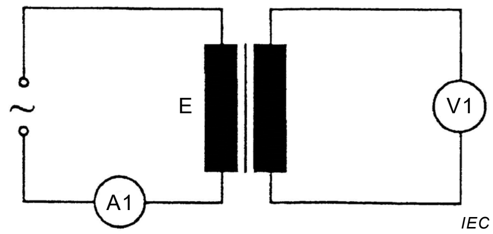
6.3.1 Peak value of magnetic polarization $\hat{J}$

The peak value of magnetic polarization, $\hat{J}$, shall be derived from the average rectified value of the secondary induced voltage measured as described in 4.7 and using formula (2) in 5.3.

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

6.3.2 RMS value of the magnetizing current (of the magnetic field strength)

The r.m.s. value of the magnetizing current shall be measured by a current measuring device responsive to r.m.s. values in the circuit as shown in Figure 4.



Components

V1 average type voltmeter

A1 current measuring device

E Epstein frame

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

Figure 4 – Circuit for measuring r.m.s. value of the magnetizing current

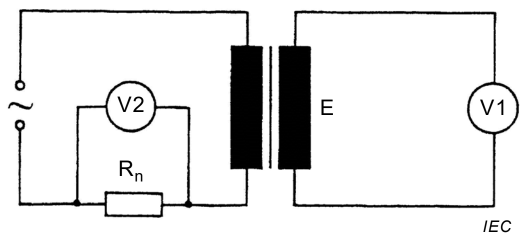
6.3.3 Peak value of magnetic field strength

6.3.3.1 General

The peak value of magnetic field strength shall be derived from the peak value of the magnetizing current, $\hat{I}_1$, measured by one of the following methods:

6.3.3.2 Method A

The peak value of the magnetizing current, $\hat{I}_1$, shall be determined by measuring the voltage drop across a known non-inductive precision resistor R_n using a peak voltmeter as shown in Figure 5.



Components

V1 average type voltmeter

V2 peak voltmeter

R_n non-inductive precision resistor

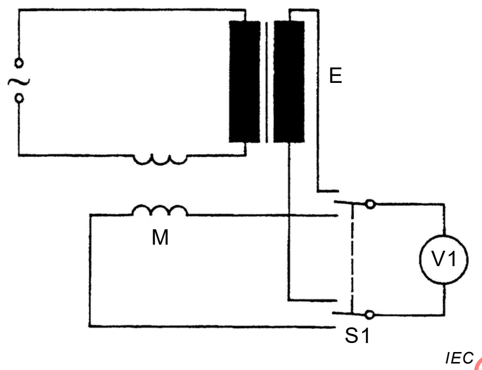
E Epstein frame

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

Figure 5 – Circuit for measuring the peak value of magnetic field strength using a peak voltmeter

6.3.3.3 Method B

The peak value of the magnetizing current, $\hat{I}_1$, shall be determined by measuring the average rectified voltage appearing across the secondary winding of a mutual inductor of an accuracy of ± 0,5 %, the primary winding of which is connected in series with the primary winding of the Epstein frame, by using an average type voltmeter in accordance with the circuit given in Figure 6.



Components

V1 average type voltmeter

M mutual inductor

S1 switch

E Epstein frame

NOTE 1 In this case, the voltmeter can be the same instrument as is used for measuring the secondary induced voltage unless there are more than two zero crossings of the voltage per period, in which case a phase controlled average type voltmeter is used.

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

Figure 6 – Circuit for measuring the peak value of magnetic field strength using a mutual inductor M

6.4 Apparatus

6.4.1 Average rectified voltage measurement

To measure the average rectified value of the secondary induced voltage and, in the case of Method B, of the mutual inductor, an average type voltmeter with at least 1 000 Ω/V internal resistance shall be used. The accuracy of the instrument used shall be of accuracy ± 0,5 % or better (see 4.7).

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

6.4.2 Current measurement

The r.m.s. value of the magnetizing current shall be measured by a current measuring device responsive to r.m.s. values. The accuracy of the instrument used shall be of accuracy ± 0,5 % or better (see 4.8).

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

6.4.3 Peak current measurement

The measurement of the peak value of the voltage drop across resistor R_n according to Method A shall be achieved either by means of an electronic voltmeter of high sensitivity responsive to peak values, or by means of a calibrated oscilloscope. The full-scale error of the device used shall be ± 3 % or better.

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

6.4.4 Resistor R_n

Method A requires a non-inductive precision resistor of an accuracy of ± 0,5 %.

The resistance value to be chosen depends upon the sensitivity of the peak voltmeter. It shall not exceed 1 W when using an Epstein frame with N_1 = 200 turns in order to minimize distortion of the induced voltage waveform.

6.4.5 Mutual inductor M_D

The mutual inductor of the circuit shown in Figure 6 shall be calibrated and its mutual inductance, M_D, determined within ± 0,5 %; the primary impedance of this inductor shall be as low as possible. To minimize errors, the secondary impedance of the inductor shall be low compared to that of the measuring instrument connected to it.

During calibration and use of the inductor, care shall be taken that measurements will not be affected by the leakage flux of the Epstein frame or other apparatus.

6.5 Measuring procedure

The test specimen shall be prepared as for 5.2.

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

If the magnetic field strength is specified and magnetic polarization is to be determined, the magnetizing current shall be set to give the relevant magnetic field strength (see below). Then the secondary induced voltage shall be read on the average type voltmeter (see 5.3).

Alternatively, if the magnetic polarization is specified and magnetic field strength is to be determined, the secondary induced voltage shall be set to its specified value as described in 5.3.

For the determination of the r.m.s. value of the magnetic field strength, $\tilde{H}$, the magnetizing current shall be read on the current measuring device.

For the determination of the peak value of magnetic field strength, $\hat{H}$, according to Method A, the peak value of the voltage drop across resistor R_n shall be read on the peak voltmeter.

According to Method B, the average rectified voltage at the secondary winding of the mutual inductor M shall be read on the average type voltmeter.

6.6 Determination of the peak value of magnetic polarization $\hat{J}$

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

$$\hat{J} = \frac{1}{4 f N_2 A} \overline{|U_2|} \qquad (6)$$

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

$$\frac{R_\mathrm{i} + R_\mathrm{t}}{R_\mathrm{i}} \tag{7}$$

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 of the Epstein frame;

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

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

R_t is the series resistance of the secondary windings of the Epstein frame and mutual inductor, in ohms;

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

6.7 Determination of the r.m.s. value of magnetic field strength $\tilde{H}$

The r.m.s. value of magnetic field strength, $\tilde{H}$, shall be calculated from the r.m.s. value of magnetizing current indicated by the current measuring device according to the circuit of Figure 4.

$$\tilde{H} = \frac{N_1}{l_\mathrm{m}} \tilde{I}_1 \tag{8}$$

where:

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

N_1 is the number of turns of the primary winding of the Epstein frame;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,94 m);

$\tilde{I}_1$ is the r.m.s. value of the magnetizing current, in amperes.

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

6.8 Determination of the peak value of magnetic field strength $\hat{H}$

If measuring Method A has been used, the peak value of magnetic field strength shall be calculated from the reading $\hat{U}_\mathrm{R}$ of the peak voltmeter:

$$\hat{H} = \frac{N_1}{R l_\mathrm{m}} \hat{U}_\mathrm{R} \tag{9}$$

where:

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

R is the resistance value of the non-inductive precision resistor R_n in Figure 5, in ohms;

$\hat{U}_\mathrm{R}$ is the peak value of the voltage drop across the non-inductive precision resistor R_n, in volts.

In the case of measuring Method B, $\hat{H}$ shall be calculated from the reading $\overline{|U_m|}$ of the average type voltmeter (but see note to 6.3.3.3) in conjunction with the mutual inductor M_D:

$$\hat{H} = \frac{N_1}{4fMl_m} \cdot \frac{R_i + R_m}{R_i} \cdot \overline{|U_m|} \tag{10}$$

where:

M is the mutual inductance in the circuit given in Figure 6, in henries;

R_m is the resistance of the secondary winding of the mutual inductor M , in ohms;

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

$\overline{|U_m|}$ is the average rectified value of the voltage induced in the secondary winding of the mutual inductor M , in volts.

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

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

$$\mu_r = \frac{\hat{J}}{\mu_0 \hat{H}} + 1$$

6.9 Determination of the specific apparent power S_s

The apparent power is given by:

$$S = \tilde{I}_1 \cdot \tilde{U}_2 \cdot \frac{N_1}{N_2} = \tilde{I} \cdot 1{,}111 \cdot \overline{|U_2|} \cdot \frac{N_1}{N_2} \tag{11}$$

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

where:

S is the apparent power, in voltamperes;

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

Division of this quantity by the effective mass, m , in accordance with formula (1), gives the specific apparent power:

$$S_s = \frac{S}{m_a} = \frac{\tilde{I} \cdot 1{,}111 \cdot \overline{|U_2|} \cdot 4lN_1}{ml_m N_2} \tag{12}$$

where:

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

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

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

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

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

N_1 is the total number of turns of the primary winding of the Epstein frame;

N_2 is the total number of turns of the secondary winding of the Epstein frame;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,94 m);

$\widetilde{I}_1$ is the r.m.s. value of magnetizing current, in amperes.

6.10 Reproducibility

The reproducibility of the results obtained from the procedure described in Clause 6 depends essentially upon the uncertainty of the instruments used for the measurement, and upon careful attention to the physical details of the test equipment. When using instruments of an accuracy of ± 0,5 %, the reproducibility of the method is characterized by a relative standard deviation of the order of 3 %.

7 Test report

The test report shall include the following, as applicable:

a) type and identity of test specimen;
b) density of material (conventional, or as measured in accordance with IEC 60404-13);
c) length of test specimen strips;
d) number of strips;
e) ambient temperature during the measurements;
f) frequency of the magnetization;
g) values of the magnetic polarization;
h) results of the measurements.

Annex A
(informative)

Epstein frame for use at medium frequencies

At medium frequencies, the energy loss arising from the dielectric loss of the material used for the winding formers and from the interwinding capacitance of the Epstein frame becomes significant.

The dielectric loss can be reduced to a negligible proportion by selecting a material of low permittivity. Polystyrene is such a material and may easily be cut and cemented to provide the required formers, terminal posts and baseplate of the Epstein frame.

Since measurements at medium frequencies are usually restricted to low loss material operating at comparatively low magnetic polarization, it is possible to reduce the number of turns and diameter of wire of the windings. In addition, by making the primary and secondary a spaced single layer winding, with equal spaces between the primary and secondary turns, the interwinding capacitance can be reduced to a minimum.

For an Epstein frame constructed in accordance with 4.4 and the above recommendations, the interwinding capacitance for 200 turns of 0,125 mm diameter wire on both the primary and secondary windings has been found to be approximately 300 pF and the resistance of each winding approximately 3,5 Ω.

The additional loss introduced by this capacitance is given by:

$$\Delta P = 1{,}111 \cdot \frac{\overline{|U_2|}^2}{Z_{ic}} \qquad \text{(A.1)}$$

Where

ΔP is the additional loss induced by the capacitance, in watts;

$Z_{ic} = \dfrac{R_i}{1 + 2\pi f C R_i}$;

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

C is the interwinding capacitance, in farads.

At low magnetic polarizations, this quantity will probably be negligible but if it reaches significant proportions, then it should be deducted from the calculated loss given in formula (4).

Annex B
(informative)

Digital sampling method for the determination of the magnetic properties

B.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 standard. Applied to the wattmeter method, it is characterized by the digitization of the secondary induced voltage, $U_2(t)$ and the voltage drop across the non-inductive precision resistor in series with the primary winding (see Figure 5), $U_1(t)$ (corresponds to U_R in formula (9)), and by the evaluation of these data for the determination of the magnetic properties of the test specimen. For this purpose, instantaneous values of these voltages having index j, u_{2J} and u_{1J} respectively, are sampled and held simultaneously from the time-dependent voltage signals during a narrow and equidistant time period each by sample-and-hold circuits. They are then immediately converted to digital values by analogue-to-digital converters (ADC). The data pairs sampled over one or more periods together with the 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.

Whilst the digital sampling method has perfectly proved its worth applied with the technical frequency range, it is expected that it will be effectively applicable to medium frequencies, i.e. that it can be applied to the measurement procedures which are described in the main part of this standard. This expectation is based on the recent availability of fast sample and hold electronics. The block diagram in Figure 3 applies equally to the analogue methods and the digital sampling method; the digital sampling method allows all functions of the measurement equipment in Figure 3 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 induced voltage can also be realized by a digital method. However, the purpose and procedure of this technique are different from those of this Annex B and are not treated here. More information can be found in [1] and [2][1].

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

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

$$\Delta t = \frac{T}{n} = \frac{1}{f \cdot n} = \frac{1}{f_s} \quad \text{(B.1)}$$

where:

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

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

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

1 Numbers in square brackets refer to the Bibliography.