IEC 62044-3

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REDLINE VERSION

INTERNATIONAL STANDARD

colour inside

Cores made of soft magnetic materials – Measuring methods –
Part 3: Magnetic properties at high excitation level

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CORES MADE OF SOFT MAGNETIC MATERIALS – MEASURING METHODS –

Part 3: Magnetic properties at high excitation level

FOREWORD

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC 62044-3:200. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC 62044-3 has been prepared by IEC technical committee 51: Magnetic components, ferrite and magnetic powder materials. It is an International Standard.

This second edition cancels and replaces the first edition published in 2000. This edition constitutes a technical revision.

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

a) addition of Annex F and Annex G.

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

Draft	Report on voting
51/1426/CDV	51/1439/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 62044 series, published under the general title *Cores made of soft magnetic materials – Measuring methods*, 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- withdrawn,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
- amended.

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INTRODUCTION

IEC 62044, under the general title *Cores made of soft magnetic materials – Measuring methods,* includes the following parts:

IEC 62044-1: Generic specification

IEC 62044-2: Magnetic properties at low excitation level

IEC 62044-3: Magnetic properties at high excitation level

CORES MADE OF SOFT MAGNETIC MATERIALS – MEASURING METHODS –

Part 3: Magnetic properties at high excitation level

1 Scope

This part of IEC 62044 ~~provides~~ specifies measuring methods for power loss and amplitude permeability of magnetic cores forming the closed magnetic circuits intended for use at high excitation levels in inductors, chokes, transformers and similar devices for power electronics applications.

The methods given in this document can cover the measurement of magnetic properties for frequencies ranging practically from direct current to 10 MHz, and even possibly higher, for the calorimetric and reflection methods. The applicability of the individual methods to specific frequency ranges is dependent on the level of accuracy that is to be obtained.

The methods in this document are basically the most suitable for sine-wave excitations. Other periodic waveforms can also be used; however, adequate accuracy can only be obtained if the measuring circuitry and instruments used are able to handle and process the amplitudes and phases of the signals involved within the frequency spectrum corresponding to the given ~~induction~~ magnetic flux density and field strength waveforms with only slightly degraded accuracy.

NOTE It ~~may~~ can be necessary for some magnetically soft metallic materials to follow specific general principles, customary for these materials, related to the preparation of specimens and ~~prescribed~~ specified calculations. These principles are formulated in IEC 60404-8-6.

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(221):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 221: Magnetic materials and components*~~
~~Amendment 1 (1993)~~
~~Amendment 2 (1999)~~

~~IEC 60205:1966, *Calculation of the effective parameters of magnetic piece parts*~~

~~IEC 60367-1:1982, *Cores for inductors and transformers for telecommunications – Part 1: Measuring methods*~~

~~IEC 60401:1993, *Ferrite materials – Guide on the format of data appearing in manufacturers' catalogues of transformer and inductor cores*~~

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

~~IEC 61332:1995, *Soft ferrite material classification*~~

IEC 62044-1:2002, *Cores made of soft magnetic materials – Measuring methods – Part 1: Generic specification*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply in addition to those of IEC 60050(221).

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

3.1.1

(effective) amplitude permeability (symbols: amplitude permeability: μ_a, effective amplitude permeability: μ_{ea})

effective amplitude permeability

μ_{ea}

magnetic permeability obtained from the peak value of the effective magnetic induction flux density, $\hat{B}_e$, and the peak value of the effective magnetic field strength, $\hat{H}_e$, at the stated value of either, when the magnetic induction flux density and magnetic field vary periodically with time and with an average of zero, and the material is initially in a specified neutralized demagnetized state

NOTE 1 This definition differs from that of IEC 60050 [221-03-07].

NOTE 2 Two amplitude permeabilities are in common use, namely:

– that in which the peak values apply to the actual waveforms of the induction and field strength,

– that in which the peak values apply to the fundamental components of waveforms of the induction and the field strength.

NOTE 3 The induction and the field strength and, consequently, the amplitude permeability may even be quasi-static quantities, provided the core is cyclically magnetized and no excursion of the B-H curve appears.

3.1.2

maximum (effective) amplitude permeability

$\mu_{ea\ max}$

maximum value of the (effective) amplitude permeability when the amplitude of excitation ($\hat{B}_e$ or $\hat{H}_e$) is varied

NOTE This definition differs from that of IEC 60050 [221-03-10].

3.1.3

excitation

either induction magnetic flux density or field strength for which the waveform and amplitude both remain within the specified tolerance

Note 1 to entry: When the induction magnetic flux density (field strength) mode of excitation is chosen, the resultant waveform of field strength (induction magnetic flux density) may can be distorted with respect to the excitation waveform due to the non-linear behaviour of the magnetic material.

3.1.4

high excitation level

excitation at which the permeability depends on excitation amplitude (particularly at low frequencies) and/or at which the power loss results in a noticeable temperature rise (particularly at high frequencies), or both

~~3.1.5~~
~~sinusoidal excitation~~
~~excitation of harmonic content of less than 1 %~~

3.1.5
exciting winding
winding of measuring coil to which the exciting voltage is applied or through which the exciting current is flowing

3.1.6
voltage sensing winding
unloaded winding of a measuring coil across which the electromotive force induced by the excitation ~~may~~ can be determined

3.1.7
measuring winding
winding, usually secondary, loaded or unloaded, which can be used for measurement apart from the exciting ~~and/~~or voltage sensing winding, or both

3.1.8
power loss
power absorbed by the core

3.1.9
pulse excitation without biasing field
excitation in which a core is energized by a voltage pulse, from a remanent flux density to a higher value of flux density in the same direction, and in which the core recovers to the same remanent flux density

Note 1 to entry: The excursion in the B-H plane associated with such a pulse is shown in Figure 1.

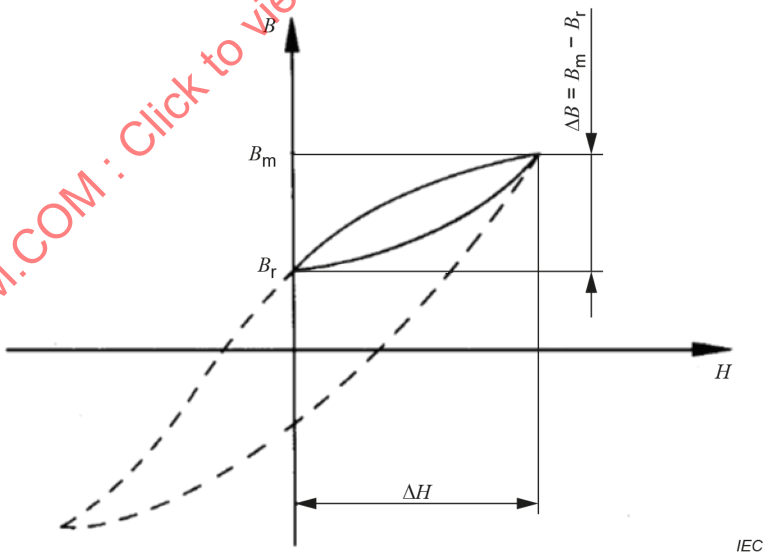


Figure 1 – Pulse excitation without biasing field

Note 2 to entry: If the back-e.m.f. during recovery is limited only by the time constant of the test circuit, then the magnetizing current decays exponentially.

Alternatively the back-e.m.f. can be limited to a constant value, for example by returning the energy via a secondary winding to a voltage source; then the magnetizing current decay is approximately linear. The latter method can prevent excessively high back-e.m.f. and high rates of change of flux. The distinction is mainly relevant to loss measurements.

3.1.10
pulse excitation with biasing field
excitation in which a core is energized by a voltage pulse, from a value of the flux density determined by a biasing field to a flux density in the opposite direction, and in which the core recovers to the same value determined by the biasing field

Note 1 to entry: The excursion in the B-H plane associated with such a pulse is shown in Figure 2.

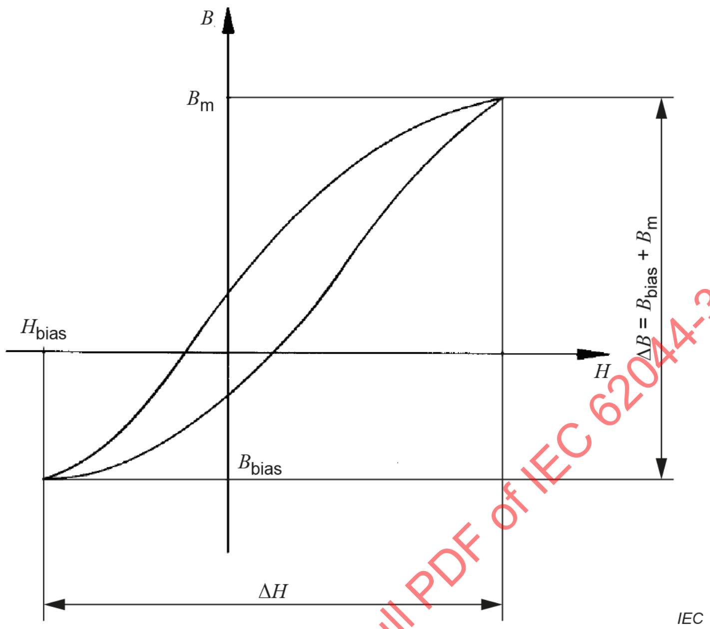


Figure 2 – Pulse excitation with biasing field

Note 2 to entry: See Note to entry 2 of 3.1.9.

3.1.11
pulse permeability
μ_p
relative permeability obtained from the change of flux density and the corresponding change of the field strength when either quantity is varying in an arbitrary form between stated limits:

$$\mu_p = \frac{1}{\mu_0} \cdot \frac{\Delta B}{\Delta H}$$

SEE: Figure 1 and Figure 2.

Note 1 to entry: The value of the pulse permeability depends strongly on the limits of the flux density or field strength excursions; it is not necessary for these limits to be symmetrical with respect to zero.

Note 2 to entry: Often pulse permeability refers to the special case of square voltage pulses being applied to an exciting winding; the flux density waveform is then approximately triangular.

3.1.12
pulse amplitude
U_m
maximum instantaneous value which an ideal voltage pulse would have with respect to the steady value of the voltage between pulses

Note 1 to entry: An ideal pulse is derived from an actual voltage pulse by ignoring unwanted or non-pertinent phenomena such as overshoot (see Figure 1).

3.1.13
pulse duration
t_d
time interval during which the instantaneous value of the pulse exceeds 50 % of the pulse amplitude

$$L_p = \frac{U_m}{\Delta i_m / t_d}$$

where

L_p is the pulse inductance

Δi_m is the total change in i_m during the pulse

SEE: Figure F.1.

Note 1 to entry: For unidirectional drive pulses $\Delta i_m = \hat{i}_m$.

3.1.14
pulse inductance factor
A_{LP}
pulse inductance divided by the square of the number of turns of the test coil

$$A_{LP} = \frac{L_p}{N^2}$$

3.1.15
voltage-time product limit
$(U \cdot t)_{lim}$
specified limit of the product of the amplitude of a voltage pulse and the time elapsed from the start of the pulse

Note 1 to entry: Within this limit the non-linearity of the magnetizing current through the measuring coil placed on the core should not exceed a specified value.

3.1.16
non-linearity (with time)
ratio of the actual instantaneous value of a characteristic at a time t to the value reached by the extrapolated linear portion of its graph versus time, at the same instant

SEE: Figure F.3.

3.1.17
pulse repetition rate
frequency of recurrence of the pulses in a periodic sequence of pulses

3.2 Symbols

All the formulae in this document use basic SI units. When multiples or sub-multiples are used, the appropriate power of 10 shall be introduced.

A_e effective cross-sectional area of the core

$\hat{B}_e$ peak value of the effective ~~induction~~ magnetic flux density in the core

f frequency

$\hat{H}_e$ peak value of the effective magnetic field strength in the core

l_e effective magnetic path length of the core

L inductance

i instantaneous value of the current

I current

N number of turns of winding of the measuring coil

P power loss in the core

~~Q_e~~ Q quality factor of the core for a given frequency

R resistance

t time

T temperature

u instantaneous value of the voltage

U voltage

V_e effective volume of the core

δ relative error, deviation, etc.

Δ absolute error, deviation, etc.

μ_{ea} ~~(~~effective~~)~~ amplitude permeability

μ_0 ~~magnetic constant~~ permeability of vacuum: approximately $4\pi \times 10^{-7}$ H/m

~~π the number 3,14159…~~

φ phase shift

ω angular frequency = $2\pi f$

NOTE 1 The additional subscript, upper script, etc., gives a more specific meaning to the given symbol.

NOTE 2 Symbols which are used sporadically are defined in the place where they appear in the text.

NOTE 3 Effective parameters, such as effective magnetic path length, l_e, effective cross-sectional area, A_e, and effective volume of the core, V_e, are calculated in accordance with IEC 60205.

NOTE 4 ~~In the further text of this standard, the terms induction and field strength stand for the shortened terms magnetic induction and magnetic field strength.~~ In the text of this document, the term flux density stands for the shortened term of magnetic flux density.

4 General ~~precautions~~ requirements for measurements at high excitation level

4.1 General statements

4.1.1 Relation to practice

The measuring conditions, methods and procedures shall be chosen in such a way that the measured results are suitable for predicting the performance of the core under practical circumstances. This does not imply that all these stipulations, especially those related to the excitation waveforms, have to correspond to terms encountered in practice.

4.1.2 Core effective parameters and material properties

Since the core is in general of non-uniform cross-section and generally has non-uniformly distributed windings along the core path, the measurement does not yield the amplitude permeability and the power loss of the material, but the effective values of these parameters appropriate to the effective ~~induction~~ magnetic flux density $\hat{B}_e$ and the effective field strength $\hat{H}_e$ in the core.

For the measurement of the amplitude permeability and the power loss of the material, the core shall have a ring or toroidal shape in which the ratio of the outer to the inner diameter should not be greater than 1,4 and should have windings distributed uniformly, close to the core, of inductive coupling coefficient practically equal to unity.

4.1.3 Reproducibility of the magnetic state

To obliterate various remanence and time effects in the core material, the measurement shall be made at a well-defined and reproducible magnetic state.

Any measurement under specified excitation, unless otherwise stated, is to be made at the time $t_m = t_c + \Delta t$ after the magnetic conditioning start; t_c is the time period within which the magnetic conditioning is completed and, whereupon, the specified excitation is set; Δt is the time period during which the core is kept stable under the excitation being set.

4.2 Measuring coil

4.2.1 General

Normally, a measuring coil will be used, but in principle any coaxial line, cavity or other suitable device providing the necessary interaction between the magnetic material and the electromagnetic signal, may also be used.

For measurement on toroid using coils, the turns of the measuring coil shall be distributed in such a way as to keep both the stray capacitance and the stray field as low as necessary for sufficiently accurate measurement.

For measurements made on cores assembled around a coil, the shape of the measuring coil shall correspond to that of the coils used for normal application of the core and its influence on the variation of the inductance to be measured shall be negligible.

Unless otherwise specified, the test coil complete with coil former or encapsulation, or both, shall be positioned in a coaxial way to the limb which it embraces, and the side of the coil at which the start of the winding is located shall be lightly pressed into contact with the core at one end of this limb as follows:

- for a symmetrical core, the coil assembly shall contact the core at either one end or the other;
- for a core with an air-gap that is asymmetrical because the gap has been made by grinding away material on the leg of one core half and not the other, the coil assembly shall make end contact to the half of the core that has not been ground away to create the gap.

One of the coil faces shall be marked so as to define its orientation. The coil shall be kept in the defined position during the whole measurement in order to obtain the maximum reproducibility of the measurement.

4.2.2 Number of turns

The number of turns shall be specified for each winding in relation to the measuring conditions, the equipment used and the accuracy to be obtained. The windings shall be wound as close to the core as possible, to make the coupling (magnetic flux linkage) coefficients between the measuring coil windings and the core and between the windings of measuring coil, as close to 100 % as possible.

The resistance, self-capacitance and inter-winding capacitance of windings should be as low as possible to make the related errors negligible.

In the case of ring or toroidal cores, the turns shall be distributed evenly around the core circumference.

The connectors, primarily of exciting winding, should consist of insulated strands, if this is necessary for measurements at high frequencies.

NOTE When winding a sharp-edge core, care should be taken to ensure that the wire insulation is not ruptured and, in the case of stranded wire, strands are not broken.

When winding a sharp-edge core, the wire insulation should not rupture and, in the case of stranded wire, the strands should not break.

4.2.3 Single winding and double winding

The use of a single winding both for excitation and voltage sensing is recommended if

- the coupling between the exciting winding and the voltage sensing winding is so reduced that it results in a non-negligible error in the determination of the measuring induction magnetic flux density B in the core;
- the inter-winding capacitance is too high;
- there is no measuring circuitry contra-indication against the direct connection of the exciting winding to the input(s) of measuring instruments.

NOTE When a single winding is used, it is recommended that its resistance be made as low as possible to make the winding ohmic power loss negligible compared to the power loss in the core.

The use of separate exciting and voltage sensing windings (double winding) is recommended if, for whatever reason, the exciting winding should be is galvanically separated from the voltage and the current measuring instruments, for example, to avoid a floating or DC connection to their inputs.

NOTE 1 When the exciting and voltage sensing windings are used, it is critical to make their magnetic coupling coefficient shall be as close to 100 % as possible.

NOTE 2 When the voltage needed for calculation of the induction in the core is measured across the voltage sensing winding then only the power loss in the core is determined with the exclusion of the ohmic power loss in the current-carrying (exciting) winding.

The voltage necessary for calculation of the magnetic flux density in the core is typically measured across a voltage sensing winding that is separate from the current-carrying (exciting) winding. When measuring core losses, ohmic losses in the voltage sensing winding do not affect the calculation, but ohmic losses in the current-carrying (exciting) winding shall be excluded from the core loss calculation.

NOTE 3 The use of two windings is recommended at more than 200 kHz.

4.3 Mounting of cores consisting of more than one part

A ferrite core set consisting of more than one part and which is to be assembled around the measuring coil, shall be held together with glue, tape or a clamping device throughout the measurement.

Whichever method is used to join the core parts together, it shall have the following characteristics:

- distribution of the joining force uniformly over the mating surfaces, without the introduction of bending stresses in the core;
- holding of all the core parts rigidly and without changing the position with regard to each other;

- when a specified clamping method is used, an initial over-force of about 10 % shall be applied when the core is closed, in order to break down fine irregularities between the cleaned mating surfaces. Next, the specified clamping force ±5 % shall be applied;
- keeping the joining force constant within ±1 % during all measuring operations within all measuring conditions, including the full specified temperature range.

The mounting of such cores shall be carried out in accordance with the following instructions.

The mating surface shall be inspected for damage and cleanness. Damaged cores shall not be used. The mating surface shall be cleaned by non-abrasive means, for example, by rubbing gently on a dry washing-leather. Next, the mating surfaces shall be degreased if they have to be glued. Dust particles shall be blown off with clean dry compressed air. The mating surfaces shall never be touched with bare fingers. The core parts shall then be assembled around the measuring coil, the latter being locked in position with respect to the core by suitable means, for example, a foam-washer. The core parts are centered and glued or placed in a clamping device. The glue, if used, shall be spread evenly on the mating surface to form a film as thin as possible and then properly hardened.

In the case where the clamping device is used, the clamping force specified in the relevant specification shall be applied. The glued, taped or clamped cores shall relax under the specified conditions (see IEC 62044-1:2002, Clause 3 ~~of IEC 60367-1~~) for a long enough time ~~sufficient~~ to allow any variation of stress effects, due to clamping, gluing or taping, to become negligible.

4.4 Measuring equipment

4.4.1 Any suitable measuring equipment may be used. Examples of appropriate circuits are given in Annex A to Annex E.

In addition to any requirement specified for the particular method ~~and/~~or measuring circuit, or both, used, the following general requirements shall be met.

4.4.2 To ensure the ~~induction~~ magnetic flux density (field strength) mode of excitation, the output impedance of the exciting source shall be low (high) compared with the series impedance of the exciting winding of the measuring coil assembled with the core under test and the current sensing resistor.

4.4.3 When the sinusoidal waveform of excitation is specified, the total harmonic content of the excitation source shall be less than 1 %. When square pulses are specified, the relevant requirements of ~~clause 16 of IEC 60367-1~~ Annex F shall be met.

4.4.4 During the period of measurement, the excitation amplitude variations shall not exceed ±0,05 % and the frequency stability shall be adequate for the measuring method and the equipment used.

4.4.5 The frequency range of voltmeters and other voltage sensing instruments shall include all harmonics of the measured voltage having amplitudes of 1 % or more of their fundamentals. This frequency range shall be specified in the relevant instrument specification.

4.4.6 The voltmeters and other voltage sensing instruments used shall be high-impedance instruments, the connection of which will have only a negligible effect on the measuring circuit, especially at high frequencies. The probes of a high-input resistance and a low-input capacitance can reduce the load effects.

4.4.7 The accuracy of the voltmeters ~~and/~~or voltage sensing instruments, determined for the calibrating sinusoidal waveform, shall be within ±0,5 % for RMS and average values and ±1 % for peak values, provided that the peak factor of waveforms to be measured is within limits imposed by the instrument.

If inaccuracies exceed the above limits, only a sine-wave excitation of total harmonic content less than 1 % is recommended and

- to determine the RMS, average and peak values of sinusoidal waveforms, a true RMS sensing voltmeter of accuracy within ±1 % is recommended. The average and peak values are obtained by multiplying the indicated RMS values by the following factors: average value = 0,900 × RMS value, peak value = 1,414 × RMS value;
- to determine the RMS, average and peak values of non-sinusoidal waveforms, a digital storage and processing oscilloscope or appropriate acquisition and processing instrument shall be used. It shall be capable of capturing and processing the waveform with the sampling rate not less than 150 samples per waveform period and the resolution not less than 8 bits.

NOTE The peak factor is the ratio of the peak value to the RMS value of the measured waveform.

4.4.8 The resistance of the in-series current sensing resistor shall be known with an inaccuracy not exceeding ±1 digit on the third significant place, including possible thermal variations of the resistance. A heat-sinking or cooled base of the resistor ~~may~~ can moderate the above thermal variations.

The inductance ~~L~~ L_R of the resistor R over the frequency range specified in 4.4.5 shall not exceed a value

~~$$L \le \frac{R}{\omega_m}\sqrt{2\delta\hat{U}_R}$$~~

$$L_R \le \frac{R}{\omega_m}\sqrt{2\delta\hat{U}_R}$$

where

R	is the value of the resistor;
$\omega_m = 2\pi f_m$	f_m being equal to the highest frequency within the frequency range specified in 4.4.5;
$\delta\hat{U}_R$	is the allowable relative increase in the voltage drop $\hat{U}_R$ across the resistor R, due to the inductance L, at frequency f_m.

For example, for $\delta\hat{U}_R = 0{,}1$ %, R = 1 Ω and the highest frequency f_m = 500 kHz, the inductance L shall be less than $(2\pi \times 500 \times 10^3)^{-1} \times 1 \times (2 \times 0{,}001)^{0{,}5}$ = 14,2 nH.

The current sensing resistor can be replaced by an appropriately adapted current probe provided that this does not reduce the amplitude and phase accuracy over the frequency range as required in 4.4.5. In addition, the current probe shall be a linear device, i.e. not generating harmonics.

NOTE For the amplitude permeability measurement, it is the amplitude accuracy of the current probe which is mainly concerned.

4.4.9 All the connections between the circuit components shall be as short as possible. In addition, connections, if more than one, giving an additional non-equal phase shift shall be of equal length and of the same type. Any phase shift $\Delta\varphi$ (radian) between the channels designed as equiphase to lead the signals corresponding to the ~~induction~~ magnetic flux density and field strength over the frequency range defined in 4.4.5 shall not exceed a value

~~$$\Delta\varphi = \pm \frac{\delta P(\Delta\varphi)}{Q_c} \text{ radian}$$~~

$$\Delta\varphi = \pm\frac{\delta P(\Delta\varphi)}{Q}$$

where

$\delta P(\Delta\varphi)$ is that portion of the total inaccuracy of the power loss measurement which is related to the phase shift $\Delta\varphi$;

$Q = \frac{\omega \hat{B}_e \hat{H}_e}{2P_v}$ is the quality factor of the core under test;

$\omega = 2\pi f$ is the angular frequency;

$\hat{B}_e$ and $\hat{H}_e$ are the peak values of the effective ~~induction~~ magnetic flux density and the effective field strength in the core, respectively;

$P_v = P/V_e$ is the power-loss density; V_e is the effective volume of the core.

If a non-sinusoidal excitation is applied, the phase shifts for the harmonics involved shall be determined. Corresponding to each harmonic frequency, the values of the parameters listed above ~~have to~~ shall be used in the calculation of each harmonic frequency.

For example, $\delta P(\Delta\varphi)$ shall be within ±1 % and Q = 5 for a given core and measuring conditions. Therefore, $\Delta\varphi$ shall be within ±0,01/5 = ±0,002 radian.

4.4.10 Any contact of any intermediary connectors, joints, switches, multiplexers, etc., which is associated with the voltage or current measuring circuit, shall be able to transmit the voltages involved and the conditioning and measuring currents of values specified in the relevant specification. The contact resistance, phase shift, inductive and capacitive couplings, series impedance and parallel admittance resulting from insertion of the contact shall have only a negligible effect on the results measured over all the measuring conditions involved, including the frequency range as specified in 4.4.5.

4.4.11 Measures ~~and/~~or calibration, or both, should be taken to ensure that the resultant inaccuracy of measurement for the amplitude permeability and the power loss over all the measuring conditions does not exceed the inaccuracy specified for the given measuring method and circuit specified ~~in the appropriate annex~~.

4.4.12 A temperature-controlled environment shall be provided, capable of maintaining the thermal equilibrium between the core and that environment within specified temperature limits during the conditioning, setting, measurement and reading operations.

5 Specimens

Cores taken from normal production and forming closed magnetic circuits shall be used for the measurement.

6 Measuring procedures

6.1 General procedure

6.1.1 The core to be measured is assembled with the measuring coil in accordance with 4.3.

In the case of ring and toroidal cores, apply winding(s) in accordance with 4.2.1.

6.1.2 The core shall be placed in a temperature-controlled environment in accordance with 4.4.12. All measuring operations such as magnetic conditioning, settings and measurement shall be made after the temperature of the core is attained and maintained within allowed tolerance limits.

6.1.3 The voltages corresponding to the peak value of ~~induction~~ the magnetic flux density $\hat{B}_e$ and to the peak value of the field strength $\hat{H}_e$ at which the measurement has to be performed are calculated in accordance with the following formulae:

– for $\hat{B}_e$ excitation: $U_{av} = 4 \cdot f \cdot N \cdot A_e \cdot \hat{B}_e$

where N is equal to N_1 when a single winding (both for exciting and voltage sensing functions) is used and N is equal to N_2 when a secondary winding is used for the voltage sensing;

– for $\hat{H}_e$ excitation:

$$\hat{U}_R = \frac{R \cdot l_e \cdot \hat{H}_e}{N_1}$$

where

$\hat{U}_R$ is the peak value of the voltage across the series resistor R;

N_1 is the number of turns of the excitation winding N_1.

The symbols are defined in 3.2, and N_1 is the number of turns of the exciting winding.

NOTE 1 For the practically pure sinusoidal waveform of ~~induction~~ magnetic flux density $\hat{B}_e$, the voltage, corresponding to $\hat{B}_e$, can be measured using also RMS or peak reading voltmeters or instruments. The respective RMS, U_{rms}, and peak, $\hat{U}$, values of this voltage are calculated as

$$U_{rms} = \sqrt{2} \cdot \pi \cdot f \cdot N \cdot A_e \cdot \hat{B}_e$$

$$\hat{U} = 2 \cdot \pi \cdot f \cdot N \cdot A_e \cdot \hat{B}_e$$

NOTE 2 If the current probe is used instead of the resistor R, the peak value of the current $\hat{I}$ corresponding to $\hat{H}_e$ is calculated as ~~$\hat{I} = \hat{H}_e \cdot l_e / N_1$~~ $\hat{I} = \hat{H}_e$.

NOTE 3 If a cross-section area other than A_e is used, for example A_{min}, for the calculation of U_{av}, this ~~shall~~ will be clearly stated in the relevant specification.

6.1.4 The core is conditioned by the electrical method in accordance with ~~item 1) of 6.2 of IEC 60367-1~~ IEC 62044-1:2002, 5.2a), unless otherwise stated.

6.1.5 At the specified time t_c after the start of the conditioning, the exciting source is set, as quickly as possible, preferably within t_c = (2 ± 0,5) s for the time-dependent parameters, to the required frequency, waveform and amplitude of excitation.

~~NOTE~~ To keep the correct excitation waveform within all the measuring conditions, it should be under control. In the case of the ~~induction~~ magnetic flux density mode of excitation, the input of the control device should preferably be connected to a separate voltage sensing winding.

6.1.6 At the time t_m, the measurement readings shall be taken and then the excitation promptly turned off. The time period when the core is under specified excitation shall be as short as possible but no longer than 10 s, to prevent the core from excessive self-heating.

6.1.7 When a core is excited under pulse conditions with or without a biasing component, the respective complementary ~~stipulations of clause 16 of IEC 60367-1 shall be taken into account~~ specifications of Annex F shall be considered.

6.2 Measuring method for the ~~(~~effective~~)~~ amplitude permeability

6.2.1 Purpose

To provide a method for the measurement of the ~~(~~effective~~)~~ amplitude permeability at high excitation levels and symmetrical periodic waveforms of magnetic cores forming closed magnetic circuits.

NOTE As an alternative, the peak value of the ~~induction~~ magnetic flux density obtained at the specified peak value of the field strength or, otherwise, the peak value of the field strength at the specified peak value of the ~~induction may~~ magnetic flux density can be determined.

6.2.2 Principle of the measurement

The ~~induction~~ magnetic flux density and the field strength in a core are determined by measuring the average value of voltage per half-period across the voltage sensing winding of the measuring coil wound on the core and the peak value of the voltage across the resistor in series with the exciting winding of that coil. The measurements are carried out at specified peak values either of ~~induction~~ magnetic flux density or field strength, frequency and temperature.

6.2.3 Circuit and equipment

Any suitable equipment may be used provided that it is able to fulfil the function of the circuits shown in Annex A.

The requirements of 4.4 shall be met. Since the ~~induction~~ magnetic flux density and field strength waveforms are not critical in the case of measurement of the amplitude permeability, it will not be necessary to rigorously meet the requirements of 4.4.2 and 4.4.3 ~~need not be rigorously met~~.

~~NOTE~~ If the amplitude permeability has to be determined for the peak values of fundamental components of the waveforms of the ~~induction~~ magnetic flux density and field strength, these peak values should be measured by frequency selective instrument(s) observing the requirements of 4.4.

6.2.4 Measuring procedure

The general procedure of 6.1 shall be ~~observed~~ applied.

For the specified average value U_{av} of the voltage across the voltage sensing winding, either the peak value $\hat{U}_R$ of the voltage across the resistor R or the peak value $\hat{I}$ of the current flowing through the exciting winding is read.

For the field strength excitation, the value of U_{av} is read at the specified value of either $\hat{U}_R$ or $\hat{I}$.

NOTE When the specification requires the ~~induction~~ magnetic flux density to be measured at the specified field strength or, inversely, the field strength at the specified ~~induction~~ magnetic flux density, the specified peak value of the excitation is set, and either the resultant $\hat{B}_e$ or the resultant $\hat{H}_e$ is determined, respectively.

6.2.5 Calculation

The ~~(~~effective~~)~~ amplitude permeability is derived from

$$\mu_{ea} = \frac{\hat{B}_e}{\mu_0 \hat{H}_e} = \frac{l_e R}{4 \mu_0 f N_1 N_2 A_e} \frac{U_{av}}{\hat{U}_R}$$

$$\mu_{ea} = \frac{\hat{B}_e}{\mu_0 \cdot} = \frac{l_e R}{4 \cdot \mu_0 \cdot f \cdot N_1 \cdot N_2 \cdot A_e} \cdot \frac{U_{av}}{\hat{U}_R}$$

or if the current probe is used instead of resistor R

$$\mu_{ea} = \frac{l_e}{4 \cdot \mu_0 \cdot f \cdot N_1 \cdot N_2 \cdot A_e} \cdot \frac{U_{av}}{\hat{I}}$$

where

U_{av} is the average value of voltage across voltage sensing winding N_2;

$\hat{U}_R$ is the peak value of the voltage across the series resistor R;

$\hat{I}$ is the peak value of the current flowing ~~by~~ in the excitation winding N_1;

N_1 is the number of turns of the excitation winding N_1;

N_2 is the number of turns of the sensing winding N_2;

the remaining symbols being defined in 3.2.

NOTE If the exciting and voltage sensing functions are performed only by the primary winding N_1, N_2 is replaced by N_1 and the product N_1 N_2 is replaced by N_1^2.

6.3 Measuring methods for the power loss

6.3.1 Purpose

To provide methods for the measurement of power loss at high excitation levels and periodic waveforms in magnetic cores forming closed magnetic circuits.

6.3.2 Methods and principles of the measurements

6.3.2.1 General

The following methods are suitable according to the principle and application.

6.3.2.2 Root-mean-square method (RMS method)

This method is:

- generally applicable provided the circuit components, mounting and equipment used meet the requirements of 4.4;
- less sensitive to distorted waveforms.

The RMS value of the sum and the difference of the two voltages, the first across the unloaded measuring winding of the measuring coil assembled with the core, and the second across the resistor in series with the exciting winding of that coil, are measured by means of the true RMS voltmeter. The difference of the squares of these RMS voltages is proportional to the power loss in the core.

The related measuring procedure is given in Annex B.

6.3.2.3 Multiplying methods

6.3.2.3.1 General

These methods, based on the identical voltage-current multiplying principle, are sensitive to phase-shift errors.

The voltage related to the ~~induction~~ magnetic flux density and the voltage related to the field strength in the core are acquired, processed and multiplied by either analogue, digital or mixed way in the time or frequency domain techniques. Some of these methods are shown in Table 1.

Table 1 – Some multiplying methods and related domains of excitation waveforms, acquisition, processing

Measuring method	Domain of			Clause of Annex C
	useable excitation waveform	acquisition	processing	
V-A-W meter	Sinusoidal	Time	Time	C.5
Impedance analyzer	Sinusoidal	Not applicable	Not applicable	C.6
Digitizing	Arbitrary	Time	Time	C.7
Vector spectrum	Arbitrary	Frequency	Frequency	C.8
Cross-power	Arbitrary	Time	Frequency	C.9

The related measuring procedures are given in Annex C.

6.3.2.3.2 V-A-W (volt – ampere – watt) meter method

This method is restricted to sinusoidal excitation as defined in 4.4.3.

A V-A-W meter multiplies internally the measured voltages and gives a time average of the product of the instantaneous values of these voltages which is proportional to the power loss of the core.

6.3.2.3.3 Impedance analyzer method

This method is restricted to sinusoidal excitation as defined in 4.4.3.

The impedance analyzer determines at the fundamental frequency the vector components of the voltages related respectively to the ~~induction~~ magnetic flux density and to the field strength in the core and calculates a parallel resistance related to the power loss in the core. The square of the voltage related to the ~~induction~~ magnetic flux density divided by the parallel resistance gives the power loss in the core.

6.3.2.3.4 Digitizing method

This method is suitable for arbitrary excitation waveforms.

The measured voltages are sampled and converted into digital data by a digitizer. At each sample point the product of the voltages involved is calculated. The power loss is proportional to the average of the multiplied voltages over one cycle.

6.3.2.3.5 Vector spectrum method

This method is suitable for arbitrary excitation waveforms.

The amplitudes and the phase difference of the voltage signals are measured by a network analyzer. The measurements are made at the fundamental and harmonic frequencies of the applied voltages.

The power loss in the core is obtained by adding up the power-loss components corresponding to the fundamental and harmonic frequencies.

6.3.2.3.6 Cross-power method

This method is suitable for arbitrary excitation waveforms.

At the specified value of excitation, one or more cycles of the measured voltages are sampled and converted into digital data.

The complex spectrum of the measured cycles is computed by fast Fourier transform (FFT). The cross-power spectrum is deduced from these data.

The power loss in the core is obtained by adding up the real parts of the cross-power spectrum at each frequency.

6.3.2.4 Reflection measurement method

This method based on the measurement of the difference between forward power P_F and reflected power P_R is

- not limited to only sinusoidal excitations;
- applicable for frequencies higher than 500 kHz;
- more suitable ~~rather~~ to the ~~induction~~ magnetic flux density mode of excitation than the field strength mode of excitation.

The measurement is made using a reflection meter connected to a two-channel measurement head. A voltmeter connected in parallel to the voltage sensing winding monitors the voltage. An average value sensing voltmeter or instrument connected to a voltage sensing winding enables the peak value of the exciting ~~induction~~ magnetic flux density to be set.

NOTE For the field strength mode of excitation, the insertion of a current sensing series resistor connected in parallel to a voltage measuring instrument ~~may~~ can decrease the accuracy of the measurement.

The related measuring procedures are given in Annex D.

6.3.2.5 Calorimetric measurement methods

These methods, based on the measurement of temperature rise of the fluid in the vessel caused by power loss in the wound core, are

- especially suited for calibration purposes;
- less dependent on the measurement frequency;
- not sensitive to distorted waveforms;
- time consuming (typically several hours per measurement point).

In the state of thermal equilibrium, the power loss is determined either by measuring the temperature difference ΔT (induced by power dissipation in the wound core) across a calibrated thermal resistance or by matching this ΔT to an equal value of ΔT induced by the supply of a determinable level of power to a heating (ohmic) resistor.

In the state of non-thermal equilibrium, the desired measured temperature is used as a set point. The determination of power loss in the wound core can be made by supplying determined levels of power through an ohmic resistor with and without the supply of power to the wound core.

The related measuring procedures are given in Annex E.

7 Information to be stated

If the measurements have to be made in accordance with this document, the following information shall be stated:

1) measuring frequency(ies);
2) temperature(s) of the measurement(s) with tolerance(s);
3) mode of excitation: ~~induction~~ magnetic flux density or field strength;
4) waveform of the excitation;
5) cross-section area of the core used for calculations, if other than the effective cross-section area A_e;
6) peak value(s) of the excitation;
7) measuring method and related measuring circuit;
8) number of turns, N_1, of the exciting winding;
9) number of turns, N_2, of the voltage sensing winding (if used);
10) number of turns, N_3, of the measuring winding if such winding is required;
11) type and size of wires and arrangement of windings on the core;
12) initial amplitude of the electrically conditioning current;
13) time periods at which the excitation is set, t_c, and the measurement made, t_m, after the start of magnetic conditioning;
14) degree of accuracy;
15) results to be presented, for example a single result; a set of single results or functional characteristics, such as power loss as a function of temperature at given values of effective ~~induction~~ magnetic flux density $\hat{B}_e$ and at a given frequency ~~as parameters~~; or amplitude permeability ~~in terms~~ as a function of effective ~~induction~~ magnetic flux density at a given frequency and temperature ~~as parameters, etc~~.

~~NOTE 1~~ When the measuring ~~and/~~or test conditions (items 1) to 6)), or both, relevant to core material properties are chosen, the ~~recommendation~~ specifications given in IEC 60401-3:2015, Clause 3 and Clause 4, and in IEC 61332:2016, 4.3, should be considered.

NOTE 1 Item 10) is not required with regard to the amplitude permeability measurement.

NOTE 2 If ~~needed~~ necessary, more information can be required in detailed specifications.

8 Test report

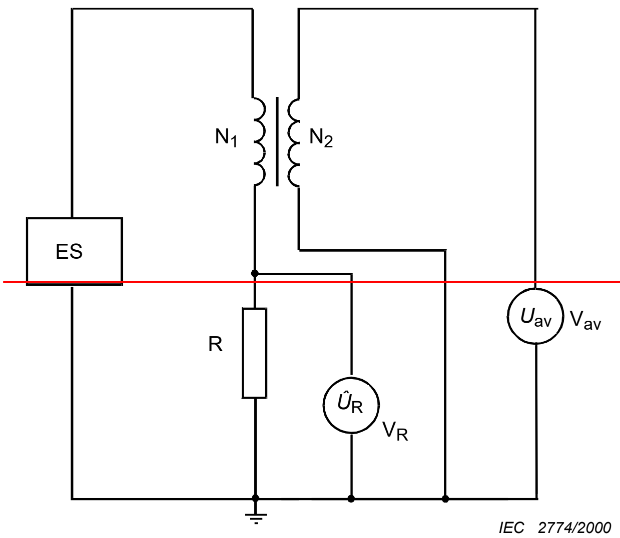
The test report shall contain as necessary:

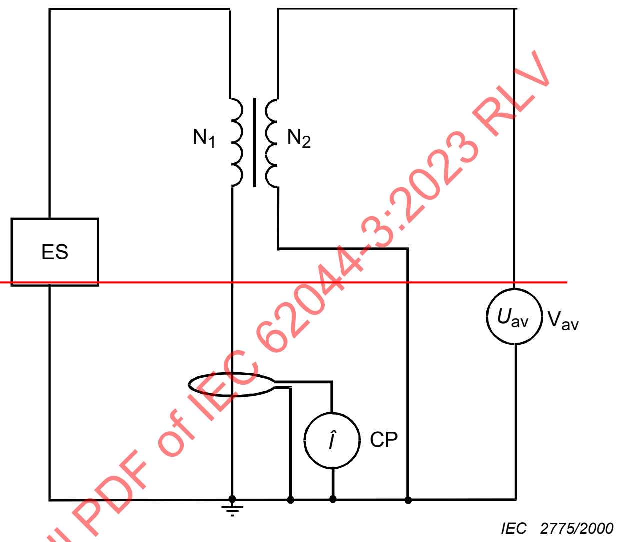
a) the statement of the test conformity with this document;
b) the type, dimensions, material and serial number or mark of the test specimen(s);
c) the sample size;
d) the parameters measured;
e) the test method used and its accuracy;
f) the test conditions (Clause 7, item 1) to item 6)).

Annex A
(informative)

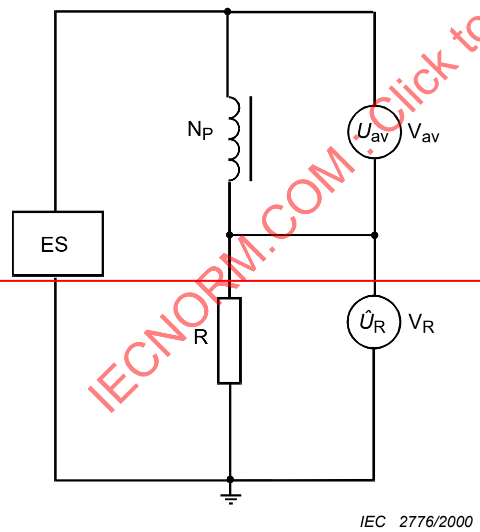
Basic circuits and related equipment for the measurement of amplitude permeability

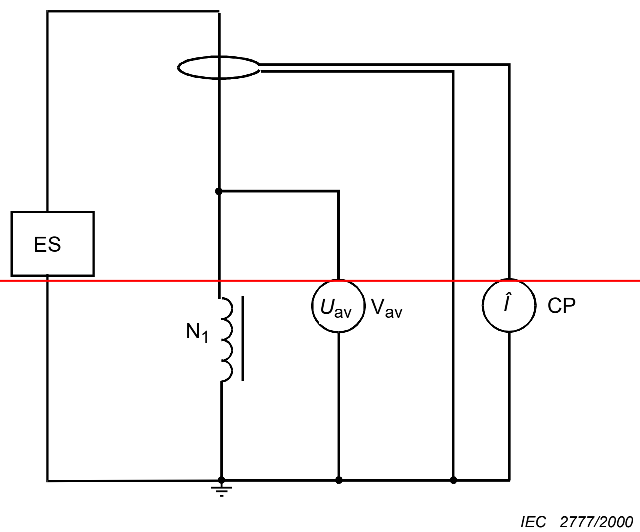
~~**Basic circuits**~~





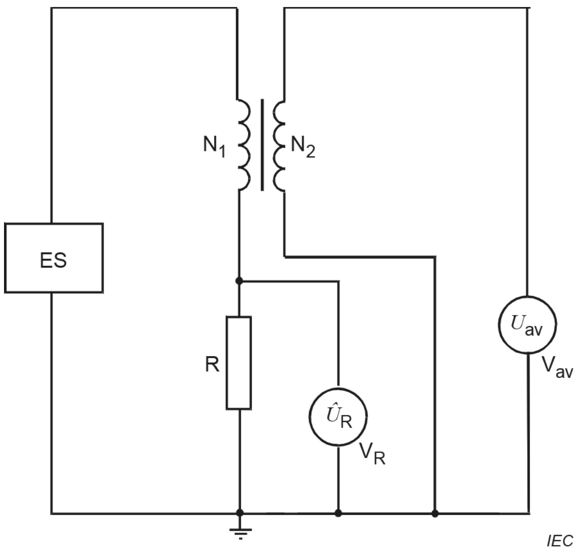
~~Circuit a)~~ ~~Circuit b)~~



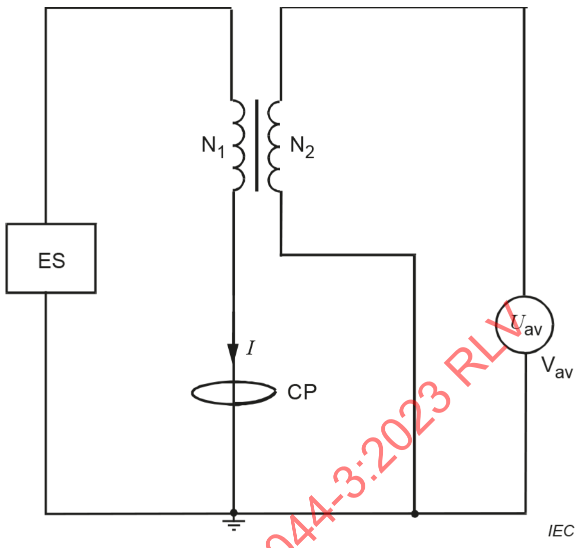


~~Circuit c)~~ ~~Circuit d)~~

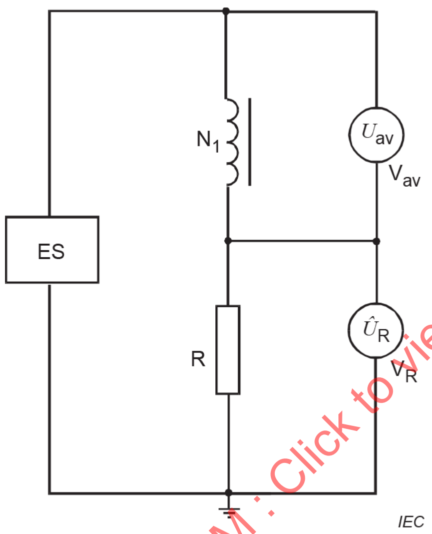
The basic circuits are shown in Figure A.1.



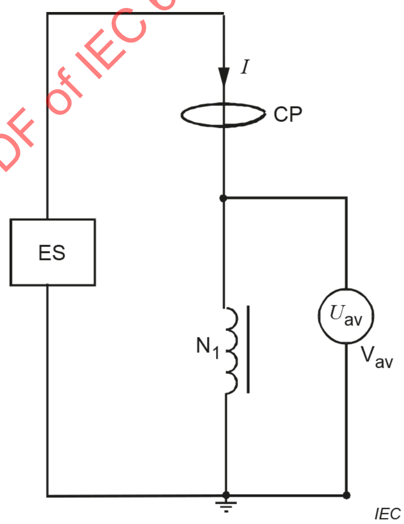
a) Circuit a)



b) Circuit b)



c) Circuit c)



d) Circuit d)

Connections and supplies

Circuit a) two windings, exciting N_1 and voltage sensing N_2, with current sensing non-reactive resistor R;

Circuit b) two windings, exciting N_1 and voltage sensing N_2, with current probe CP;

Circuit c) single exciting winding N_1 with current sensing non-reactive resistor R and floating input instruments V_{av} and V_R;

Circuit d) single exciting windings N_1 with current probe CP.

Components

ES	exciting source containing usually a generator and power amplifier;
R	resistor across which the voltage proportional to the current I flowing ~~by~~ in the exciting winding is measured;
CP	current probe sensing the peak value $\hat{I}$ of the current;
V_R	voltmeter or instrument sensing the peak value $\hat{U}_R$ of the voltage across the resistor R;
V_{av}	voltmeter or instrument sensing the average value U_{av} of the voltage;
N_1 and N_2	exciting and voltage sensing windings, respectively.

Figure A.1 – Basic circuits for the measurement of amplitude permeability

The circuits and equipment used ~~should~~ shall meet the requirements of 4.4.

The resultant accuracy within ±3 % can be obtained if the requirements of 4.4 are met.

Annex B
(informative)

Root-mean-square method for the measurement of power loss – Example of a circuit and related procedure

B.1 Method of measurement

In the RMS method, a switch S is used to connect the RMS sensing voltmeter or instrument to measure both the sum and the difference of two voltages (see Figure B.1); the short-circuiting connections of the switch shall be as close as possible to the switch and the RMS sensing voltmeter or instrument shall be connected to the switch using a low-noise, single-screened, low-capacitance cable.

It is recommended that the voltage measuring instruments V_{rms} and V_{av} be connected by means of high impedance attenuation probes to minimize a risk of transient over-voltage effects on V_{rms} and V_{av}. These effects ~~may~~ can result when the excitation is too abruptly turned ~~and/~~or the contact position of the switch S changed, or both.

The requirements of 4.4.2, 4.4.4, 4.4.9 and 4.4.10 ~~should~~ shall be met.

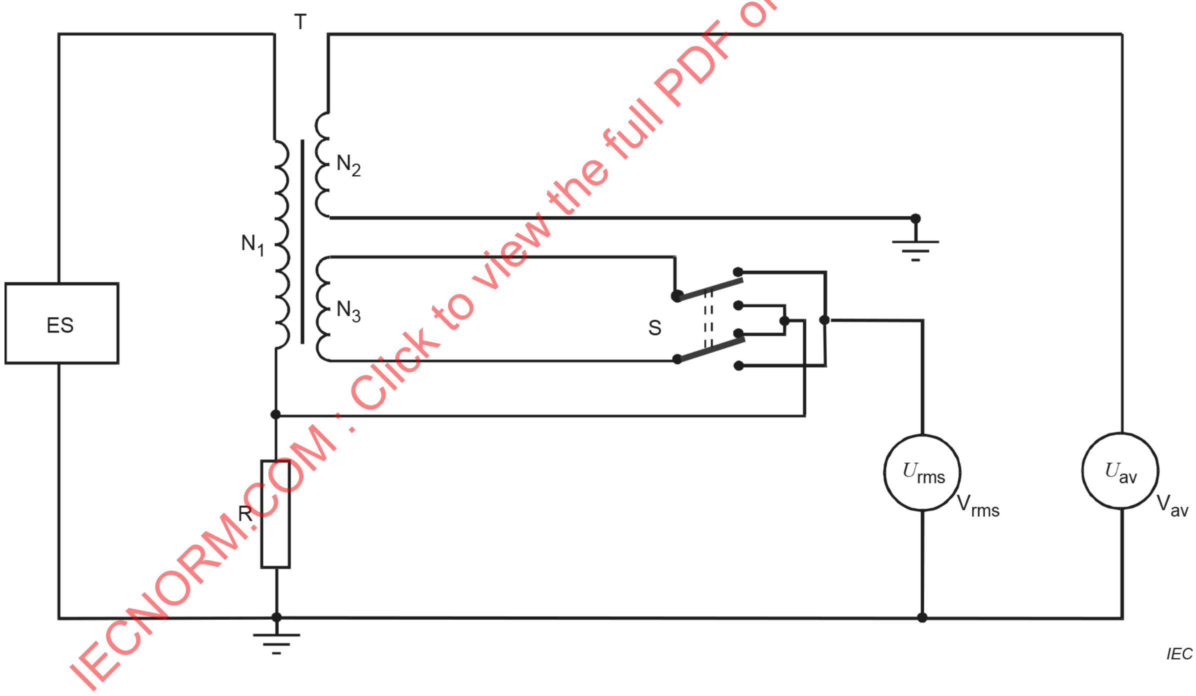


Figure B.1 – Example of a measuring circuit for the RMS method

B.2 Measuring coil

In the RMS method, a triple wound measuring coil with separate exciting winding, measuring winding and voltage sensing winding is used.

NOTE The measuring winding is used to prevent any change of the phase shift between the voltages across the measuring winding and across the resistor R, by any voltage measuring instrument. It also enables the voltmeter to be earthed.

B.3 Measuring equipment

The excitation source ES ~~should~~ shall meet the requirements specified in 4.4.3 and 4.4.4. For rectangular voltage pulses, with or without bias, the exciting source ~~should~~ shall meet the requirements of ~~16.6 of IEC 60367-1~~ Clause F.6. If the core is to be excited by waveforms other than the sinusoidal or rectangular ones, requirements modelled on those of ~~16.6 of IEC 60367-1 should~~ Clause F.6 shall be specified in the relevant specification.

The transformer T is composed of the core under test and three separate windings wound on it, N_1 being the exciting winding, N_2 being the voltage sensing winding and N_3 being the measuring winding. It is advisable to adjust the number of turns of the measuring winding N_3 so that the voltage across it is of the same order as the voltage drop across the current-measuring resistor R. The accuracy of the method increases as these voltages approach numerical equality.

V_{rms} is a true RMS voltmeter or other instrument performing that function. V_{av} is an average value sensing voltmeter or instrument. Both V_{rms} and V_{av} ~~should~~ shall meet the requirements of 4.4.5, 4.4.6 and 4.4.7.

Other requirements of 4.4 ~~should~~ shall also be met.

B.4 Measuring procedure

The general procedure of 6.1 should be met. In this method, indications of the RMS sensing voltmeter or instrument are read when it is connected to measure first the sum and then the difference of the two voltages. These readings shall be taken, as quickly as possible, so that they are only negligibly influenced by differences in the thermal state of the core and measuring coil.

The calculation is a follows:

The core power loss is given by

$$P = \overline{(u \cdot i)} = \frac{\left|U_1^2 - U_2^2\right|}{4 \cdot \frac{N_3}{N_1} \cdot R}$$

where

$\overline{(u \cdot i)}$ is the time-averaged product of the instantaneous values of the voltage induced by the excitation in the measuring coil assembled with the core and the current through the exciting winding;

U_1 is the RMS value of the sum of the voltages across the measuring winding and across the resistor R;

U_2 is the RMS value of the difference of the above voltages;

N_1 is the number of turns of the exciting winding of the measuring coil;

N_3 is the number of turns of the measuring winding of the measuring coil;

R is the value of the current-measuring resistor.

B.5 Pulse measurement and accuracy

In the case of pulse measurements, the pulse repetition frequency f_p is chosen by consideration of the recovery time. It is therefore preferable, in this case, to express the power loss in terms of energy per cycle, ~~$E = (u \cdot i)/f_p$~~ $P = \frac{\overline{(u \cdot i)}}{f_p}$. For a given pulse amplitude and pulse duration, E is independent of f_p and in general, $P = E \cdot f_p$.

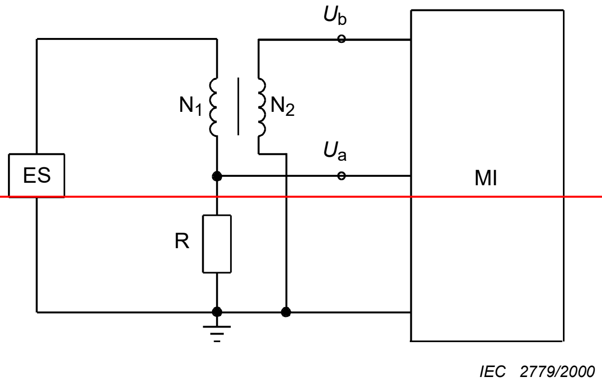
For this method, the resultant accuracy within ±5 % can be obtained for the power loss determination if the requirements of 4.4 are met.

Annex C
(informative)

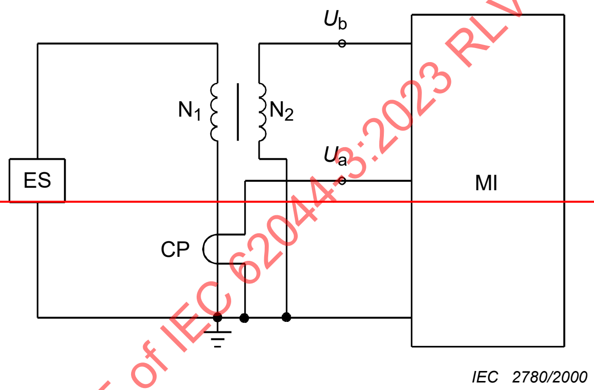
Multiplying methods for the measurement of power loss – Basic circuits and related measurement procedures

C.1 Basic circuits

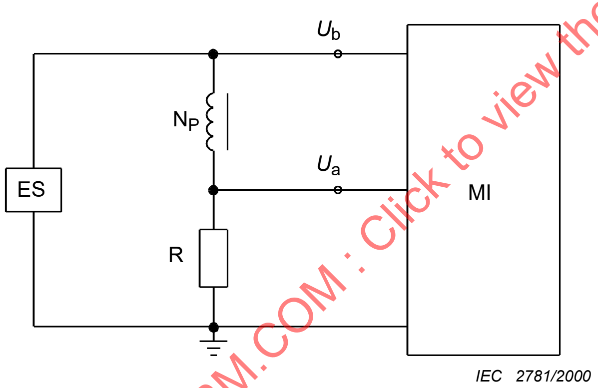
~~**Basic circuits**~~



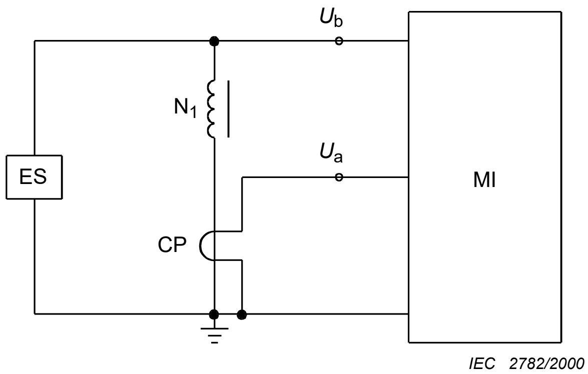
~~Circuit a)~~



~~Circuit b)~~

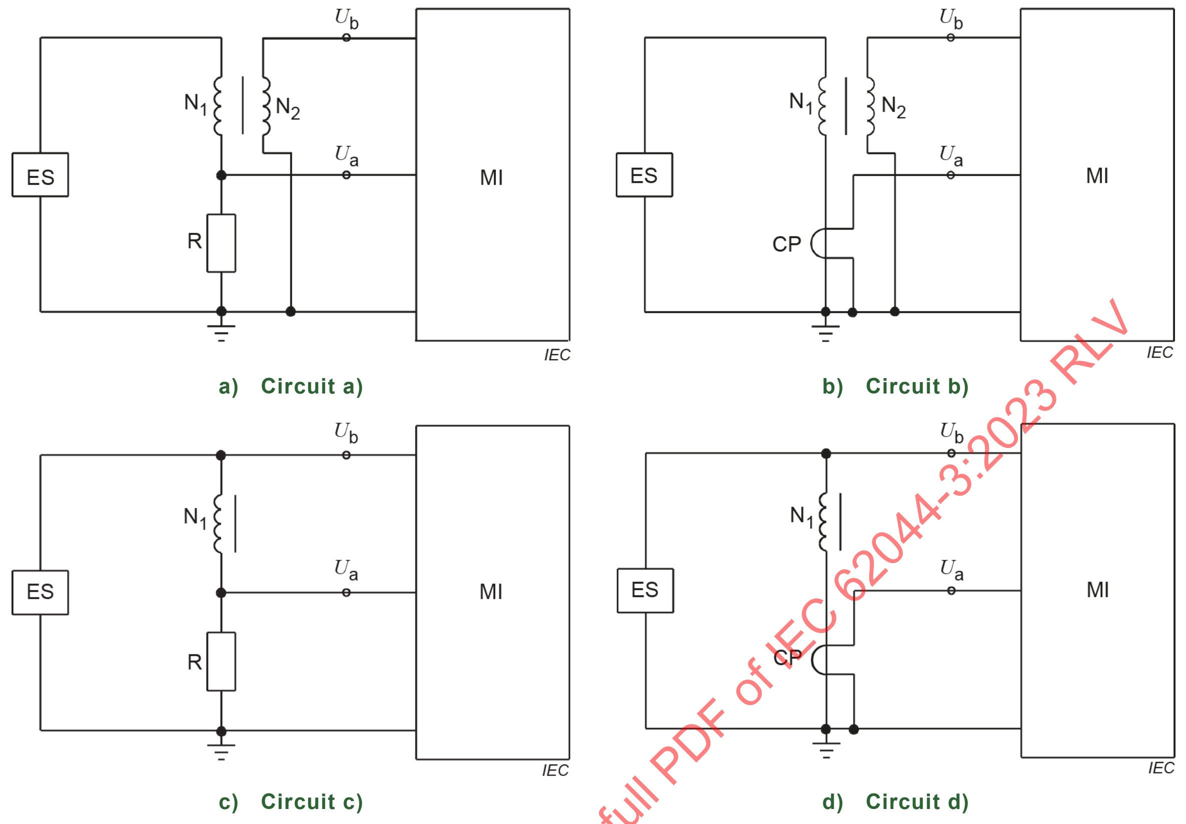


~~Circuit c)~~



~~Circuit d)~~

The basic circuits are shown in Figure C.1.



Connections and supplies

Circuit a) two windings, excitation N_1 and voltage sensing N_2 with current sensing non-reactive resistor R;

Circuit b) two windings, exciting N_1 and voltage sensing N_2 with current probe CP;

Circuit c) single excitation winding N_1 with current sensing non-reactive resistor R and floating inputs;

Circuit d) single excitation winding N_1 with current probe CP.

Components

ES excitation source;

R non-reactive current sensing resistor across which the voltage U_a, proportional to the current I flowing through the exciting winding N_1, is measured;

MI measuring instrument which fulfills the function of acquiring and processing, including the multiplication of the voltages U_a and U_b;

N_1 excitation winding;

N_2 voltage sensing winding;

U_a voltage drop proportional to the current I flowing through the exciting winding;

U_b voltage drop across either the N_1 or N_2 winding; the average value of U_b is proportional to the ~~induction~~ magnetic flux density in the core (see 4.2.2);

U_a and U_b symbolize the instantaneous, average or RMS values of the voltages, depending on the specific multiplying method.

~~NOTE 1~~ The exciting source ES normally includes the generator and power amplifier; an impedance matching adapter ~~may~~ can also be added. Exciting source ES and measuring instrument MI ~~may~~ can be integrated into one, often computer controlled, measuring unit (system).

~~NOTE 2~~ The current probe CP, if used, should be a linear device, i.e. that will not ~~to~~ generate harmonics and ~~should~~ shall comply with the ~~stipulations~~ requirements of 4.4.8.

Figure C.1 – Basic circuits for multiplying methods

C.2 Requirements

The circuits and measuring equipment used ~~should~~ shall meet the requirements of 4.4.

C.3 Measuring coil

The requirements of 4.2 ~~should~~ shall be met.

C.4 Accuracy

The ultimate accuracy of the test equipment is a complex function dependent upon measuring instruments and other characteristics of the measuring conditions and equipment; it is therefore not always possible to state the absolute accuracy that is attainable by a given multiplying instrument of a system at all measuring conditions.

Amplitude and phase measurement errors influencing strongly the accuracy of the power loss measurement can be a combination of factors related to the following errors:

- residual errors after calibration;
- errors of calibration standard;
- tracking error between two measurement channels (amplitude and phase);
- non-linearity of the instrument (for example, amplifier, mixer, A-D converter, current transformer);
- frequency error;
- accuracy of settings (for example, of flux density);
- calculation errors.

~~– etc.~~

Reference should be made to the manufacturer's instructions accompanying the instrument for ~~advice~~ guidance on errors ~~likely to~~ that can occur and their correction, ~~especially~~ particularly with respect to circuit connections and the calibration procedure.

To minimize the errors, the ~~precautions~~ requirements of Clause 4 shall be conscientiously observed and harmonized with the multiplying instrument capabilities and with the error limits corresponding to particular measuring ranges of the instrument.

C.5 V-A-W (volt-ampere-watt) meter method

The measured voltages are multiplied internally in the V-A-W meter. The V-A-W meter determines the time average of the product of the voltages which is proportional to the power loss in the core, P.

The calculation is as follows:

The power loss in watts (W) is given by the following formula:

$$P = (\overline{u \cdot i}) = \mathrm{K} \cdot \alpha$$

where

$(\overline{u \cdot i})$ is the time average of the instantaneous values of the power loss in the core;

α is the reading of the V-A-W meter;

K is the instrument constant.

C.6 Impedance analyzer method

The impedance analyzer determines the vector components of the measured voltages and calculates the equivalent parallel resistance R_p.

The calculation is as follows:

The measured power loss P in watts (W) is given by

$$P = \frac{U_{rms}^2}{R_p}$$

where

U_{rms} is the RMS value of the measured voltage across the exciting winding.

NOTE Although the measured power loss is calculated via the equivalent parallel resistance R_p, the calculation of this loss can also be related to a direct multiplication of the current and voltage signals. Therefore the measured power loss P which is equal to U_{rms}^2/R_p can also be expressed as

$$P = U_{rms} \cdot I_{rms} \cdot \cos \varphi.$$

C.7 Digitizing method

The voltages $u_a(t)$ and $u_b(t)$, according to Figure C.1, are sampled into values U_{a_i} and U_{b_i} by a digitizer, where i refers to the i^{th} sample of the signal (i = 1, 2, 3, ...).

The instantaneous power loss values at each sample point i within the sample cycle is proportional to the product $U_{a_i} \cdot U_{b_i}$.

The calculation is as follows:

With n samples for the measuring cycle the measured power loss is calculated by

$$P = \alpha \cdot \frac{1}{n} \cdot \sum_{i=1}^{n} (U_{ai} \cdot U_{bi})$$

where

α is the constant of proportionality, depending on the circuit arrangement.

C.8 Vector spectrum method

The network analyzer measures the RMS values of the fundamental and harmonic voltages U_{ak} and U_{bk} together with the phase angle ϕ_k between these voltages, where k is the k^{th} harmonic number (k = 1,2,3,..).

Calculation

The measured power loss P is given by

$$P = \alpha \cdot \sum_{k} (U_{ak} \cdot U_{bk}) \cdot \cos \varphi_k$$

where

α is the constant of proportionality, depending on the circuit arrangement.

C.9 Cross-power method

The sampling of the voltage is performed as described in the digitizing method. The voltages $\mu_a(t)$ and $\mu_b(t)$ are processed by FFT (fast Fourier transform) in order to obtain the RMS values of the fundamental and harmonic voltages: U_{ak} and U_{bk}, together with the phase angle ϕ_k between these two voltages.

The calculation is as follows:

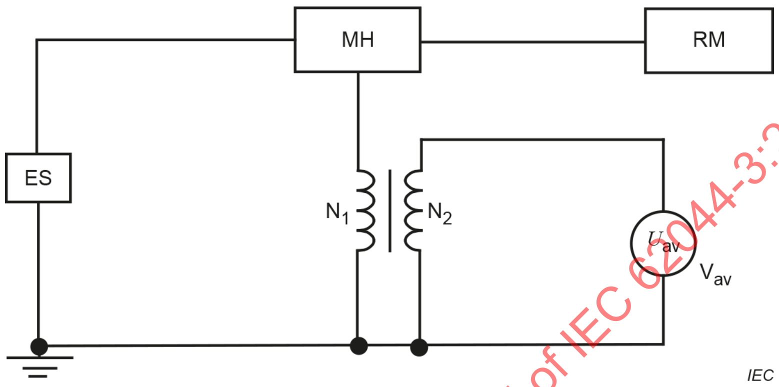
The calculation of the measured power loss is the same as for the vector spectrum method.

Annex D
(informative)

Reflection method for the measurement of power loss – Basic circuit and related measurement procedures

D.1 Basic circuit

The basic circuit is shown in Figure D.1.



Components

ES exciting source containing usually a generator and power amplifier;

RM reflection meter;

MH two-channel measurement head;

V_{av} voltmeter or instrument sensing the average value of the voltage U_{av}.

Figure D.1 – Basic circuit

D.2 Requirements

The circuits and measuring equipment ~~should~~ shall meet the requirements of 4.4. If a non-sinusoidal excitation is applied, the reflection meter shall be able to measure the components of the reflected power averaging not less than seven harmonics.

D.3 Measuring coil

The requirements of 4.2 ~~should~~ shall be met.

D.4 Measuring procedure and accuracy

The general procedure of 6.1 should be met. The forward and reflected power are read directly from the reflection meter.

The calculation is as follows:

The measured core power loss is given by

$$P = P_F - P_R$$

where

P_F is the forward power;

P_R is the reflected power.

The measurement accuracy depends on such main error factors as

- instrument errors;
- impedance mismatch.

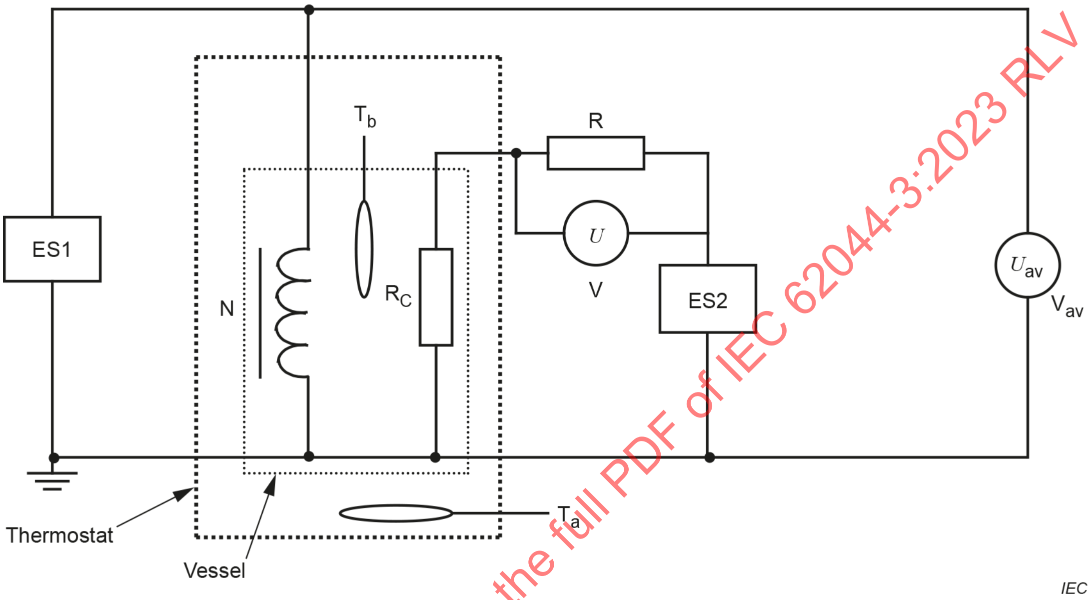
To minimize errors the ~~precautions~~ requirements of Clause 4 shall be conscientiously followed. The measurement accuracy is decreased as the subtraction result $P_F - P_R$ is decreased.

Annex E
(informative)

Calorimetric measurement methods for the measurement of power loss

E.1 Basic circuit

The basic circuit is shown in Figure E.1.



Components

ES1 excitation source for the measuring coil usually containing a generator and power amplifier;

ES2 excitation source for the heating resistor R_c usually containing a DC generator and power amplifier;

R non-reactive current sensing resistor across which the voltage U, proportional to the current I, is measured;

R_c heating resistor causing a temperature rise of the fluid in the vessel due to the dissipation of a determinable level of power;

N measuring coil;

V_{av} voltmeter or instrument sensing the average value of the voltage U_{av} across the measuring coil;

V voltmeter or instrument sensing the value of the voltage U across R;

T_a thermostat temperature sensor indicating the thermostat temperature T_a;

T_b vessel temperature sensor indicating the vessel temperature T_b.

~~NOTE 1~~ T_a ~~must~~ shall be kept stable, i.e. independent of ambient temperature, during the measurement.

~~NOTE 2~~ In order to have T_b as close as possible to the temperature of the wound core, it is recommended that a stirrer be used to achieve a homogeneous temperature distribution.

~~NOTE 3~~ The fluid in the vessel ~~must~~ shall have a small thermal capacity and a high enough boiling temperature.

~~NOTE 4~~ The fluid in the vessel should have a low permittivity and low dielectric loss at measuring frequency(ies) and temperature(s).

Figure E.1 – Basic circuit and related measurement procedures – Measurement set-up

E.2 Requirements

The circuit and measuring equipment ~~should~~ shall meet the requirements of 4.4.

E.3 Measuring coil

The general requirements of 4.2 ~~should~~ shall be met.

E.4 Accuracy

For this method the resultant accuracy of ±5 % can be obtained for power loss determination if ~~notes 1 to 4 above~~ the specifications in Figure E.1 are observed and the requirements of 4.4 met.

~~Special attention should be given to the~~ Temperature measurements should be as precise as possible because errors in the temperature measurements strongly influence the accuracy of the power loss measurement.

E.5 Measurements at thermal equilibrium

E.5.1 General

Measurements of the temperature differences ($T_a - T_b$) are made in a state of thermal equilibrium.

As the final temperature difference, induced either by power dissipation in the ohmic resistor or wound core, settles as a non-linear function of time (due to the combination of thermal resistances and thermal capacitances in the caloric measuring system), its measurement can only be made in a state of thermal equilibrium.

The measuring temperature to determine the core losses is not exactly known in advance because the final temperature difference induced by the power loss in the measuring coil is not known in advance.

NOTE If the temperature difference ($T_a - T_b$) tends exponentially with time to a constant value, then the influence of the thermal resistances and capacitances can be represented as an effect caused by a combination of one single (thermal) resistance and (thermal) capacity. For this situation, The ~~measurement of the~~ temperature difference does not need to be ~~made~~ measured only at thermal equilibrium. Measurements can be made at an earlier stage because the curve fitting of this response can be used to estimate the final temperatures of thermal equilibrium.

E.5.2 Measurement across calibrated thermal resistance

The thermal resistance R_{th} between the fluid inside the vessel and the thermostat ~~needs to~~ shall be calibrated prior to the power loss measurement and is given by

$$R_{th} = \frac{\Delta T_c}{P_c}$$

where

ΔT_c is the temperature difference between vessel and thermostat given by ($T_a - T_b$) caused by the power loss in the heating resistor R_c;

P_c is the supplied power through the heating resistor given by $I^2 R_c$.

The power loss in the wound core can be determined by

$$P = \frac{\Delta T}{R_{th}}$$

where

ΔT is the temperature difference between vessel and thermostat given by ($T_a - T_b$) caused by the power loss in the wound core;

R_{th} is the previously calibrated thermal resistance.

E.5.3 Measurement by matching the temperature rise in the core and resistor

Since the calibration of the thermal resistance is time-consuming, an alternative method consists of matching ΔT_c to ΔT by adjusting P_c.

The final temperature rise ΔT due to the core loss in the wound core is measured. Subsequently, this value is used as a set point for the final temperature rise ΔT_c due to the supplied power through the heating resistor.

E.6 Measurements at non-thermal equilibrium

The desired measuring temperature is used as a set point. This set point temperature inside the vessel can be effected in two situations caused by:

a) caused by power loss in the heating resistor only (P_{c1});

b) caused by power loss in the heating resistor and the excited core (P_{c2}).

By measuring the two levels of supplied power to the heating resistor one can obtain the power loss in the wound core (P) by

$$P = P_{c2} - P_{c1}$$

Annex F
(normative)

Magnetic properties under pulse condition

F.1 Object

To provide measuring methods for the core properties which are of importance when using cores under pulse conditions, namely: the pulse inductance factor, or pulse permeability, and the non-linearity of the magnetizing current associated with a specified voltage-time product limit.

F.2 Measurement methods

Refer to 3.1.9 to 3.1.17 for definitions of the terms relating to the measurement methods.

F.3 Principle of the methods

The core is excited by applying square voltage pulses. Two principal methods are possible:

1) The pulses are repeated with a suitable repetition frequency. The voltage across the measuring coil is rectified to eliminate the back swing and measured with an average responding voltmeter. The peak magnetizing current is also measured.
2) Both the curve of the magnetizing current as a function of time $i_m(t)$, and the loop of the voltage across the inductor integrated with respect to time as a function of the magnetizing current $\int u dt$ versus i_m, are displayed on a properly calibrated oscilloscope. This method may be used for both repeated and single pulses, the display being photographed in the latter case.

The pulse inductance factor or the pulse permeability can be determined by either method; the non-linearity of the magnetizing current associated with a specified voltage-time product limit can only be determined by the second method.

F.4 Specimens

Cores taken from normal production, and forming complete magnetic circuits, shall be used for the measurement.

F.5 Measuring coil

The number of turns should be specified in relation to the measuring conditions, the equipment used and the accuracy to be obtained. The resistance and the self-capacitance of the measuring coil at the measuring frequency should be as low as is necessary to make the error negligible. The measuring coil should be situated as closely as possible to, and uniformly along, the part or parts of the core as specified, the winding arrangement normally approximating to that used with the core in its application. In the case of a toroidal core, the turns shall be evenly distributed along the circumference.

When it is impossible to make the coil resistance small enough for the applied voltage to approximate to the e.m.f. with sufficient accuracy, then a double winding measuring coil consisting of a voltage winding and a current winding should be used. The voltage winding should have a resistance very much smaller than the impedance of the attached voltmeter and its self-capacitance should be so small that the error it causes is negligible. It should be wound as close to the core as possible and the current winding shall completely cover the voltage winding.

NOTE 1 An electrostatic screen between the two windings can be desirable.

NOTE 2 When winding a coil onto a sharp-edged core, the wire insulation will not be able to rupture.

F.6 Measuring equipment

Any suitable measuring equipment can be used. Examples of appropriate circuits for measurement with exponential recovery are given in Annex G. The following requirements shall be met:

a) Pulse generator

   When connected to the coil, the test circuit being adjusted for the appropriate back swing and recovery time, the pulse generator used for these measurements shall supply voltage pulses of the required amplitude, duration and repetition rate and meet the following general requirements:

   1) when adjusted to a given value, the pulse amplitude shall remain constant within 5 %;
   2) the power available from the source shall be sufficient to obtain a voltage pulse having a droop not exceeding 10 %;
   3) the switching shall be fast enough not to affect the rise time and the fall time significantly;
   4) the overshoot shall not exceed the specified limits.

b) Current measurement

   The current through the measuring coil (or its current winding) shall be measured by means of either:

   1) a current probe which yields a signal proportional to the current within 2 % and which, when connected to the oscilloscope, does not adversely affect the voltage pulse droop; or
   2) a precision resistor between the test coil and earth which causes a voltage drop not exceeding 1 % of the nominal pulse amplitude and has negligible inductance.

c) Recovery time

   For measurement with repeated pulses, the time constant of the measuring circuit shall be such that the recovery time is smaller than the interval between the pulses in order to ensure that the flux in the core returns to its initial value.

d) Voltmeter

   When using the average voltmeter method, the voltmeter shall be a Class 1[1] instrument or better and the diode shall be so chosen that it introduces negligible error.

1 Class index: see IEC 60051-1.

e) Oscilloscope method

When the oscilloscope method is used, the time constant of the voltage integrating circuit shall exceed 100 times the pulse duration or 100 times the effective time constant of the recovery, whichever is the greater, and its phase shift should be as small as possible.

Calibration facilities shall be provided for the display of voltage and current to obtain an overall accuracy of the measured pulse inductance factor better than 5 %.

The connecting cables to the oscilloscope shall be of a low capacitance type (e.g. air insulated cables).

F.7 Measuring procedure

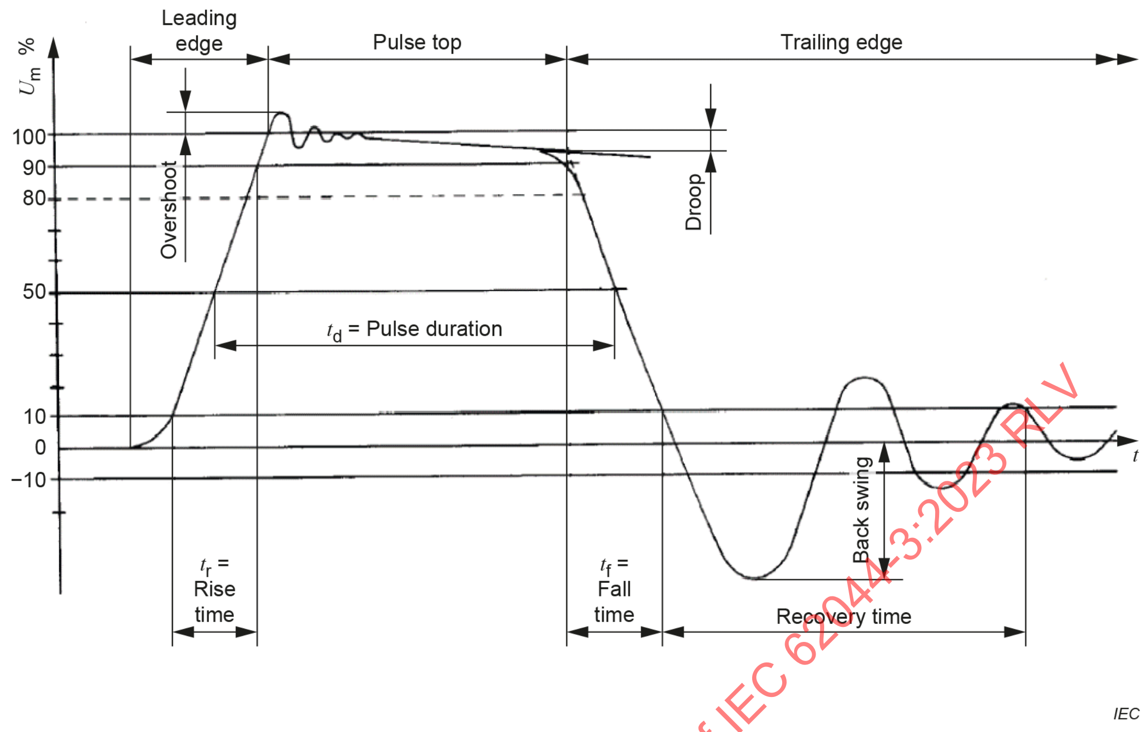
F.7.1 General

a) The core to be measured is assembled with the measuring coil in accordance with 4.2.1 and 4.3.

b) For measurement with repeated pulses, the pulse repetition rate is so chosen that the self-heating of the coil and the core is negligible.

c) The generator is checked to ensure that it will meet the specified voltage pulse characteristics, the measuring coil being replaced by a resistor which has a resistance approximately equal to the absolute value of the coil impedance under pulse conditions. Figure F.1 shows a pulse with exaggerated distortion for the purpose of defining the relevant parameters.

In the pulse as displayed on the oscillograph, a straight line shall be drawn exactly coinciding with the steady voltage between pulses, and a straight line or a simple curve of the exponential type coinciding with most of the pulse top. The intersection of this latter line with the actual pulse leading edge gives the pulse amplitude U_m. Lines are drawn parallel to the time axis at -10 %, +10 %, +50 %, +80 % and +90 % of U_m. A straight line is drawn through the points where the pulse reaches 0,9 U_m for the last time and next reaches 0,1 U_m; when the droop is nearly 10 % of U_m, however, the value of 0,8 U_m shall be used instead of 0,9 U_m. The intersection of this line with that drawn on the pulse top is the border between pulse top and trailing edge.



NOTE For clarity in illustrating the droop, the 80 % and 10 % points have been used in constructing the line which determines the border between the pulse top and the trailing edge.

Figure F.1 – Voltage pulse parameters

F.7.2 Measurement of pulse inductance factor and magnetizing current

a) For measurement without bias, a measuring coil conforming with Clause F.5 shall be used. For measurement with bias, an additional bias winding having a specified number of turns shall be wound over the measuring coil, and connected to a DC power supply through an impedance of such magnitude that the bias winding has no appreciable effect on the value of the current through the measuring coil.

When making measurements with a biasing field, the direct current I_b in the bias winding is adjusted to correspond to the specified value of the biasing field strength H_b:

$$I_b = \frac{H_b \cdot l_e}{N_b}$$

where:

l_e is the effective magnetic path length of the core;

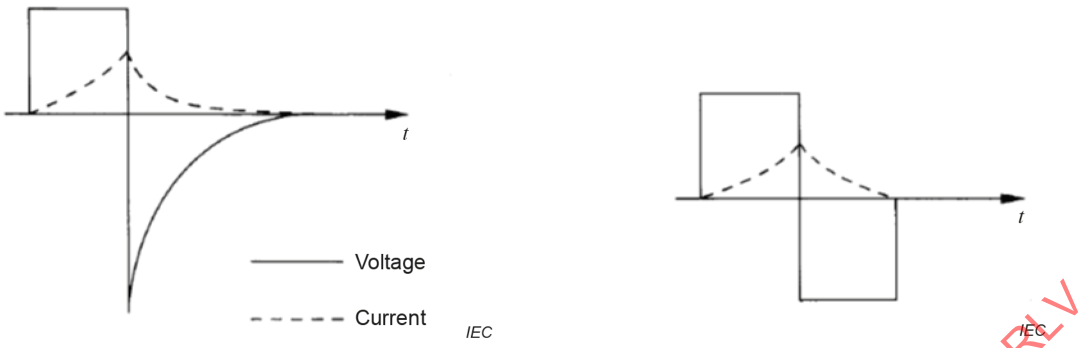
N_b is the number of turns of the bias winding of the measuring coil.

NOTE 1 Reference is often made to the biasing ampere-turns:

$$I_b N_b = H_b \cdot l_e$$

b) The measuring circuit is adjusted to give the specified voltage pulse characteristics including pulse duration and recovery time.

NOTE 2 With the coil connected in the measuring circuit, the voltage pulse waveform for exponential and linear recovery will appear typically as in Figure F.2.



a) **Exponential recovery** b) **Linear recovery**

Figure F.2 – Typical measuring waveforms

The applied pulse voltage amplitude is then increased, maintaining the specified pulse characteristics, to give a reading on the average reading voltmeter or on the oscilloscope corresponding to the specified flux change $\Delta\Phi$ in the core as indicated below:

– for measurements with repeated pulses $u_{av} = N \cdot \Delta\Phi \, f_p$.

– for measurements with isolated pulses $\int u \, dt = N \cdot \Delta\Phi$

where:

N is number of turns of the measuring coil winding connected to the voltmeter or oscilloscope;

f_p is the pulse repetition rate.

For measurements with repeated pulses the pulse shape and repetition frequency are checked and adjusted when necessary, and the average voltage u_{av} and the peak magnetizing current $\hat{i}_m$ are recorded.

For measurements with isolated pulses the displayed loop of $\int u \, dt$ versus i_m is photographed, if possible in such a way that the calibration voltage pulses in both co-ordinates are included, and the total excursion of $\int u \, dt$ and the corresponding variation of magnetizing current are recorded.

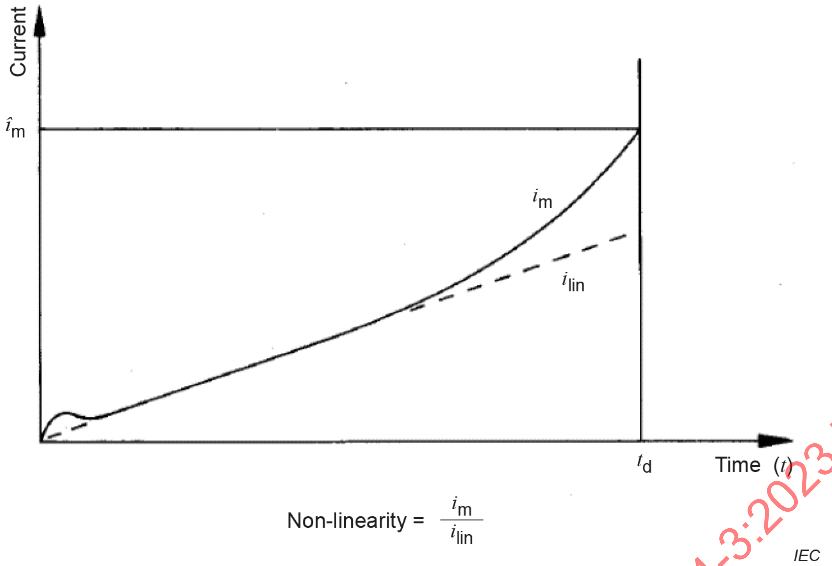
NOTE 3 A better accuracy can be obtained when use is made of a digital processing method.

F.7.3 Measurement of the non-linearity of the magnetizing current

This measurement is made to determine that the claimed value of non-linearity of the magnetizing current is not exceeded at the specified voltage-time product limit.

NOTE Typical values of non-linearity lie between 1 and 1,5.

Voltage pulses, repeated or isolated, are applied to the measuring coil as in F.7.2. The magnetizing current is displayed on an oscilloscope as a function of time, the display being photographed if necessary. The voltage pulse amplitude is varied until its voltage-time product equals the specified limit value and the non-linearity of the magnetizing current at the end of the pulse is determined (see Figure F.3).



See 3.1.16.

Figure F.3 – Non-linearity of magnetizing current

F.8 Calculation

a) Pulse inductance factor

The pulse inductance factor is calculated from one of the following expressions:

$$A_{LP} = \frac{u_{av}}{f_p \cdot \hat{\imath}_m \cdot N^2} \quad \text{or} \quad A_{LP} = \frac{\int u dt}{\hat{\imath}_m \cdot N^2}$$

where:

$\int u dt$ is the voltage across the measuring coil integrated over the pulse duration (i.e. the total excursion);

u_{av} is the average (half-wave) rectified voltage across the measuring coil;

f_p is the pulse repetition frequency;

$\hat{\imath}_m$ is the peak value of the magnetizing current;

N is the number of turns of the measuring coil winding connected to the voltmeter or oscilloscope.

b) Non-linearity of magnetizing current

In the graph of the magnetizing current as a function of time, recorded as described in F.7.3, the linear portion of the curve is extrapolated. In Figure F.3 the curve labelled i_m shows the original graph and the line labelled i_{lin} shows the extrapolated linear portion of it.

The non-linearity of the magnetizing current, defined as $\frac{i_m}{i_{lin}}$ when measured at time t_d shall not exceed the specified value, corresponding to the specified voltage-time product limit, which for the conditions of measurement described in F.7.3 is given by:

$$(U \cdot t)_{lim} = U_m \cdot t_d$$

c) Pulse inductance factor at voltage-time product limit

The pulse inductance factor corresponding to the specified value of the voltage-time product limit is calculated from the expression:

$$A_{LP} = \frac{(U \cdot t)_{lim}}{\hat{\imath}_m \cdot N^2} = \frac{U_m \cdot t_d}{\hat{\imath}_m \cdot N^2}$$

where the symbols have the meanings given in a) and the values of $\hat{\imath}_m$ and U_m are those corresponding to the method of F.7.3.

Annex G
(informative)

Examples of circuits for pulse measurements

The circuit to be chosen depends upon the conditions to be realized:

- measurement with or without bias;
- measurement with isolated pulses or with repeated pulses.

Figure G.1 shows a circuit suitable for measurement without bias and for isolated pulses; Figure G.2 shows a circuit suitable for measurement with bias and for repeated pulses. The circuits for measurement with bias and isolated pulses, and for measurement without bias and repeated pulses can easily be developed from these examples.

In the case of measurement with repeated pulses, a resistor should be added in parallel with the measuring coil as in Figure G.2. This load resistor R_L has been shown in series with a diode which blocks the current through it during the pulse duration period, in order to conserve power and to avoid excessive dissipation. The value of R_L should be high enough to obtain a recovery time smaller than the interval between the pulses, but not so high that the back swing is excessive.

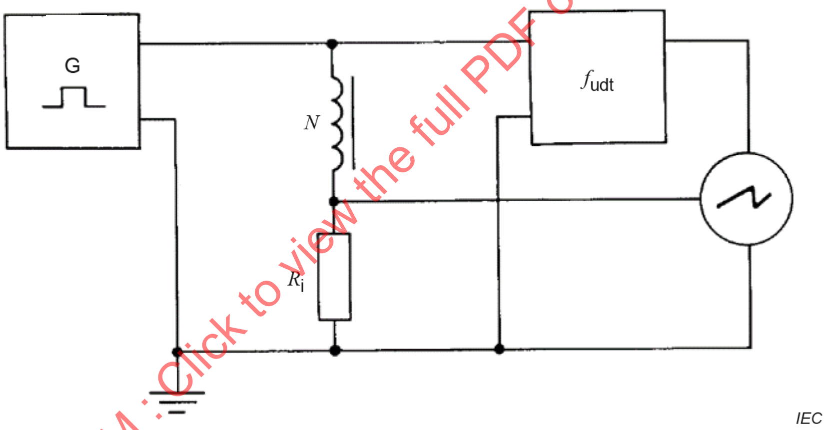


Figure G.1 – Measurement without bias and with single pulses

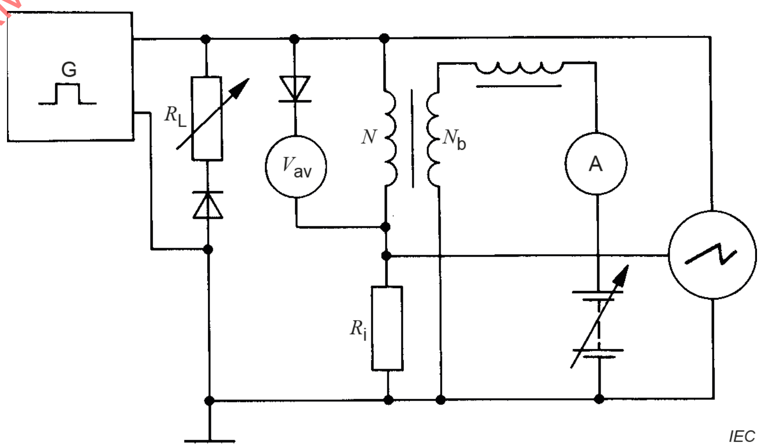


Figure G.2 – Measurement with bias and with repeated pulses

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IEC 60205, *Calculation of the effective parameters of magnetic piece parts*

IEC 60401-3:2015, *Terms and nomenclature for cores made of magnetically soft ferrites – Part 3: Guidelines on the format of data appearing in manufacturers catalogues of transformer and inductor cores*

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

IEC 61332:2016, *Soft ferrite material classification*

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IEC 62044-3

Edition 2.0 2023-07

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Cores made of soft magnetic materials – Measuring methods – Part 3: Magnetic properties at high excitation level

Noyaux en matériaux magnétiques doux – Méthodes de mesure – Partie 3: Propriétés magnétiques à niveau élevé d'excitation

IEC 62044-3:2023-07(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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CORES MADE OF SOFT MAGNETIC MATERIALS – MEASURING METHODS –

Part 3: Magnetic properties at high excitation level

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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IEC 62044-3 has been prepared by IEC technical committee 51: Magnetic components, ferrite and magnetic powder materials. It is an International Standard.

This second edition cancels and replaces the first edition published in 2000. This edition constitutes a technical revision.

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

a) addition of Annex F and Annex G.

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

Draft	Report on voting
51/1426/CDV	51/1439/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 62044 series, published under the general title *Cores made of soft magnetic materials – Measuring methods*, 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
- amended.

INTRODUCTION

IEC 62044, under the general title *Cores made of soft magnetic materials – Measuring methods,* includes the following parts:

IEC 62044-1: Generic specification

IEC 62044-2: Magnetic properties at low excitation level

IEC 62044-3: Magnetic properties at high excitation level

CORES MADE OF SOFT MAGNETIC MATERIALS – MEASURING METHODS –

Part 3: Magnetic properties at high excitation level

1 Scope

This part of IEC 62044 specifies measuring methods for power loss and amplitude permeability of magnetic cores forming the closed magnetic circuits intended for use at high excitation levels in inductors, chokes, transformers and similar devices for power electronics applications.

The methods given in this document can cover the measurement of magnetic properties for frequencies ranging practically from direct current to 10 MHz, and even possibly higher, for the calorimetric and reflection methods. The applicability of the individual methods to specific frequency ranges is dependent on the level of accuracy that is to be obtained.

The methods in this document are basically the most suitable for sine-wave excitations. Other periodic waveforms can also be used; however, adequate accuracy can only be obtained if the measuring circuitry and instruments used are able to handle and process the amplitudes and phases of the signals involved within the frequency spectrum corresponding to the given magnetic flux density and field strength waveforms with only slightly degraded accuracy.

NOTE It can be necessary for some magnetically soft metallic materials to follow specific general principles, customary for these materials, related to the preparation of specimens and specified calculations. These principles are formulated in IEC 60404-8-6.

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 62044-1:2002, *Cores made of soft magnetic materials – Measuring methods – Part 1: Generic specification*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions 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

3.1.1
effective amplitude permeability
μ_{ea}
magnetic permeability obtained from the peak value of the effective magnetic flux density, $\hat{B}_e$, and the peak value of the effective magnetic field strength, $\hat{H}_e$, at the stated value of either, when the magnetic flux density and magnetic field vary periodically with time and with an average of zero, and the material is initially in a specified demagnetized state

3.1.2
maximum effective amplitude permeability
$\mu_{ea\ max}$
maximum value of the effective amplitude permeability when the amplitude of excitation ($\hat{B}_e$ or $\hat{H}_e$) is varied

3.1.3
excitation
either magnetic flux density or field strength for which the waveform and amplitude both remain within the specified tolerance

Note 1 to entry: When the magnetic flux density (field strength) mode of excitation is chosen, the resultant waveform of field strength (magnetic flux density) can be distorted with respect to the excitation waveform due to the non-linear behaviour of the magnetic material.

3.1.4
high excitation level
excitation at which the permeability depends on excitation amplitude (particularly at low frequencies) or at which the power loss results in a noticeable temperature rise (particularly at high frequencies), or both

3.1.5
exciting winding
winding of measuring coil to which the exciting voltage is applied or through which the exciting current is flowing

3.1.6
voltage sensing winding
unloaded winding of a measuring coil across which the electromotive force induced by the excitation can be determined

3.1.7
measuring winding
winding, usually secondary, loaded or unloaded, which can be used for measurement apart from the exciting or voltage sensing winding, or both

3.1.8
power loss
power absorbed by the core

3.1.9
pulse excitation without biasing field
excitation in which a core is energized by a voltage pulse, from a remanent flux density to a higher value of flux density in the same direction, and in which the core recovers to the same remanent flux density

Note 1 to entry: The excursion in the B-H plane associated with such a pulse is shown in Figure 1.

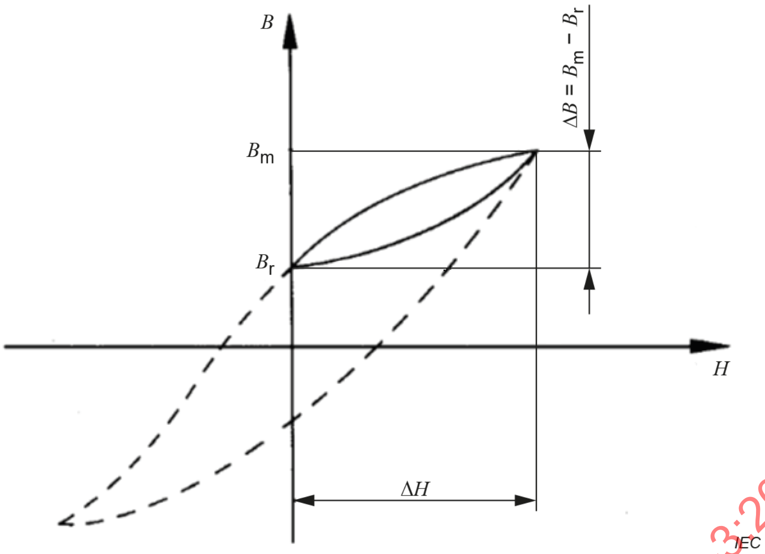


Figure 1 – Pulse excitation without biasing field

Note 2 to entry: If the back-e.m.f. during recovery is limited only by the time constant of the test circuit, then the magnetizing current decays exponentially.

Alternatively the back-e.m.f. can be limited to a constant value, for example by returning the energy via a secondary winding to a voltage source; then the magnetizing current decay is approximately linear. The latter method can prevent excessively high back-e.m.f. and high rates of change of flux. The distinction is mainly relevant to loss measurements.

3.1.10
pulse excitation with biasing field

excitation in which a core is energized by a voltage pulse, from a value of the flux density determined by a biasing field to a flux density in the opposite direction, and in which the core recovers to the same value determined by the biasing field

Note 1 to entry: The excursion in the B-H plane associated with such a pulse is shown in Figure 2.

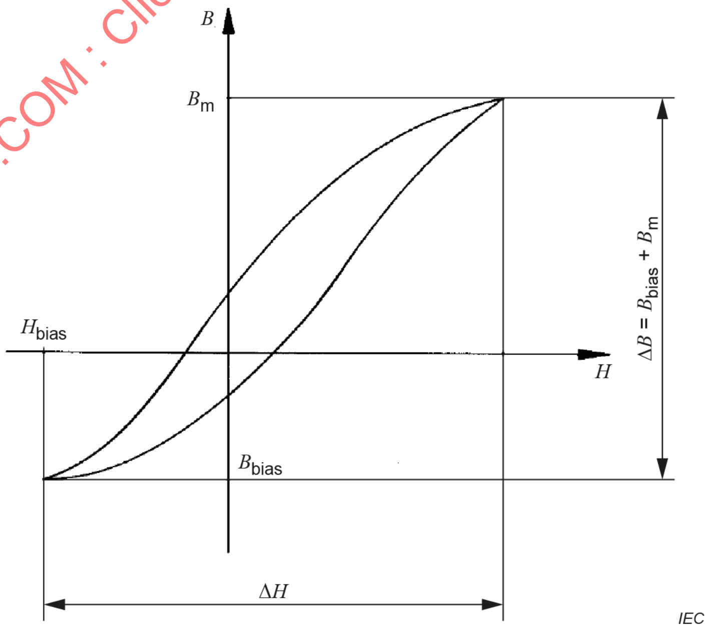


Figure 2 – Pulse excitation with biasing field

Note 2 to entry: See Note to entry 2 of 3.1.9.

3.1.11
pulse permeability
μ_p
relative permeability obtained from the change of flux density and the corresponding change of the field strength when either quantity is varying in an arbitrary form between stated limits:

$$\mu_p = \frac{1}{\mu_0} \cdot \frac{\Delta B}{\Delta H}$$

SEE: Figure 1 and Figure 2.

Note 1 to entry: The value of the pulse permeability depends strongly on the limits of the flux density or field strength excursions; it is not necessary for these limits to be symmetrical with respect to zero.

Note 2 to entry: Often pulse permeability refers to the special case of square voltage pulses being applied to an exciting winding; the flux density waveform is then approximately triangular.

3.1.12
pulse amplitude
U_m
maximum instantaneous value which an ideal voltage pulse would have with respect to the steady value of the voltage between pulses

Note 1 to entry: An ideal pulse is derived from an actual voltage pulse by ignoring unwanted or non-pertinent phenomena such as overshoot (see Figure 1).

3.1.13
pulse duration
t_d
time interval during which the instantaneous value of the pulse exceeds 50 % of the pulse amplitude

$$L_p = \frac{U_m}{\Delta i_m / t_d}$$

where

L_p is the pulse inductance

Δi_m is the total change in i_m during the pulse

SEE: Figure F.1.

Note 1 to entry: For unidirectional drive pulses $\Delta i_m = \hat{i}_m$.

3.1.14
pulse inductance factor
A_{LP}
pulse inductance divided by the square of the number of turns of the test coil

$$A_{LP} = \frac{L_p}{N^2}$$

3.1.15
voltage-time product limit
$(U \cdot t)_{lim}$
specified limit of the product of the amplitude of a voltage pulse and the time elapsed from the start of the pulse

Note 1 to entry: Within this limit the non-linearity of the magnetizing current through the measuring coil placed on the core should not exceed a specified value.

3.1.16
non-linearity (with time)
ratio of the actual instantaneous value of a characteristic at a time t to the value reached by the extrapolated linear portion of its graph versus time, at the same instant

SEE: Figure F.3.

3.1.17
pulse repetition rate
frequency of recurrence of the pulses in a periodic sequence of pulses

3.2 Symbols

All the formulae in this document use basic SI units. When multiples or sub-multiples are used, the appropriate power of 10 shall be introduced.

A_e	effective cross-sectional area of the core
$\hat{B}_e$	peak value of the effective magnetic flux density in the core
f	frequency
$\hat{H}_e$	peak value of the effective magnetic field strength in the core
l_e	effective magnetic path length of the core
L	inductance
i	instantaneous value of the current
I	current
N	number of turns of winding of the measuring coil
P	power loss in the core
Q	quality factor of the core for a given frequency
R	resistance
t	time
T	temperature
u	instantaneous value of the voltage
U	voltage
V_e	effective volume of the core
δ	relative error, deviation, etc.
Δ	absolute error, deviation, etc.
μ_{ea}	effective amplitude permeability
μ_0	permeability of vacuum: approximately $4\pi \times 10^{-7}$ H/m
φ	phase shift
ω	angular frequency = $2\pi f$

NOTE 1 The additional subscript, upper script, etc., gives a more specific meaning to the given symbol.

NOTE 2 Symbols which are used sporadically are defined in the place where they appear in the text.

NOTE 3 Effective parameters, such as effective magnetic path length, l_e, effective cross-sectional area, A_e, and effective volume of the core, V_e, are calculated in accordance with IEC 60205.

NOTE 4 In the text of this document, the term flux density stands for the shortened term of magnetic flux density.

4 General requirements for measurements at high excitation level

4.1 General statements

4.1.1 Relation to practice

The measuring conditions, methods and procedures shall be chosen in such a way that the measured results are suitable for predicting the performance of the core under practical circumstances. This does not imply that all these stipulations, especially those related to the excitation waveforms, have to correspond to terms encountered in practice.

4.1.2 Core effective parameters and material properties

Since the core is in general of non-uniform cross-section and generally has non-uniformly distributed windings along the core path, the measurement does not yield the amplitude permeability and the power loss of the material, but the effective values of these parameters appropriate to the effective magnetic flux density $\hat{B}_e$ and the effective field strength $\hat{H}_e$ in the core.

For the measurement of the amplitude permeability and the power loss of the material, the core shall have a ring or toroidal shape in which the ratio of the outer to the inner diameter should not be greater than 1,4 and should have windings distributed uniformly, close to the core, of inductive coupling coefficient practically equal to unity.

4.1.3 Reproducibility of the magnetic state

To obliterate various remanence and time effects in the core material, the measurement shall be made at a well-defined and reproducible magnetic state.

Any measurement under specified excitation, unless otherwise stated, is to be made at the time $t_m = t_c + \Delta t$ after the magnetic conditioning start; t_c is the time period within which the magnetic conditioning is completed and, whereupon, the specified excitation is set; Δt is the time period during which the core is kept stable under the excitation being set.

4.2 Measuring coil

4.2.1 General

Normally, a measuring coil will be used, but in principle any coaxial line, cavity or other suitable device providing the necessary interaction between the magnetic material and the electromagnetic signal, may also be used.

For measurement on toroid using coils, the turns of the measuring coil shall be distributed in such a way as to keep both the stray capacitance and the stray field as low as necessary for sufficiently accurate measurement.

For measurements made on cores assembled around a coil, the shape of the measuring coil shall correspond to that of the coils used for normal application of the core and its influence on the variation of the inductance to be measured shall be negligible.

Unless otherwise specified, the test coil complete with coil former or encapsulation, or both, shall be positioned in a coaxial way to the limb which it embraces, and the side of the coil at which the start of the winding is located shall be lightly pressed into contact with the core at one end of this limb as follows:

- for a symmetrical core, the coil assembly shall contact the core at either one end or the other;
- for a core with an air-gap that is asymmetrical because the gap has been made by grinding away material on the leg of one core half and not the other, the coil assembly shall make end contact to the half of the core that has not been ground away to create the gap.

One of the coil faces shall be marked so as to define its orientation. The coil shall be kept in the defined position during the whole measurement in order to obtain the maximum reproducibility of the measurement.

4.2.2 Number of turns

The number of turns shall be specified for each winding in relation to the measuring conditions, the equipment used and the accuracy to be obtained. The windings shall be wound as close to the core as possible, to make the coupling (magnetic flux linkage) coefficients between the measuring coil windings and the core and between the windings of measuring coil, as close to 100 % as possible.

The resistance, self-capacitance and inter-winding capacitance of windings should be as low as possible to make the related errors negligible.

In the case of ring or toroidal cores, the turns shall be distributed evenly around the core circumference.

The connectors, primarily of exciting winding, should consist of insulated strands, if this is necessary for measurements at high frequencies.

When winding a sharp-edge core, the wire insulation should not rupture and, in the case of stranded wire, the strands should not break.

4.2.3 Single winding and double winding

The use of a single winding both for excitation and voltage sensing is recommended if

– the coupling between the exciting winding and the voltage sensing winding is so reduced that it results in a non-negligible error in the determination of the measuring magnetic flux density B in the core;
– the inter-winding capacitance is too high;
– there is no measuring circuitry contra-indication against the direct connection of the exciting winding to the input(s) of measuring instruments.

When a single winding is used, it is recommended that its resistance be made as low as possible to make the winding ohmic power loss negligible compared to the power loss in the core.

The use of separate exciting and voltage sensing windings (double winding) is recommended if, for whatever reason, the exciting winding is galvanically separated from the voltage and the current measuring instruments, for example, to avoid a floating or DC connection to their inputs.

When the exciting and voltage sensing windings are used, their magnetic coupling coefficient shall be as close to 100 % as possible.

The voltage necessary for calculation of the magnetic flux density in the core is typically measured across a voltage sensing winding that is separate from the current-carrying (exciting) winding. When measuring core losses, ohmic losses in the voltage sensing winding do not affect the calculation, but ohmic losses in the current-carrying (exciting) winding shall be excluded from the core loss calculation.

The use of two windings is recommended at more than 200 kHz.

4.3 Mounting of cores consisting of more than one part

A ferrite core set consisting of more than one part and which is to be assembled around the measuring coil, shall be held together with glue, tape or a clamping device throughout the measurement.

Whichever method is used to join the core parts together, it shall have the following characteristics:

- distribution of the joining force uniformly over the mating surfaces, without the introduction of bending stresses in the core;
- holding of all the core parts rigidly and without changing the position with regard to each other;
- when a specified clamping method is used, an initial over-force of about 10 % shall be applied when the core is closed, in order to break down fine irregularities between the cleaned mating surfaces. Next, the specified clamping force ±5 % shall be applied;
- keeping the joining force constant within ±1 % during all measuring operations within all measuring conditions, including the full specified temperature range.

The mounting of such cores shall be carried out in accordance with the following instructions.

The mating surface shall be inspected for damage and cleanness. Damaged cores shall not be used. The mating surface shall be cleaned by non-abrasive means, for example, by rubbing gently on a dry washing-leather. Next, the mating surfaces shall be degreased if they have to be glued. Dust particles shall be blown off with clean dry compressed air. The mating surfaces shall never be touched with bare fingers. The core parts shall then be assembled around the measuring coil, the latter being locked in position with respect to the core by suitable means, for example, a foam-washer. The core parts are centered and glued or placed in a clamping device. The glue, if used, shall be spread evenly on the mating surface to form a film as thin as possible and then properly hardened.

In the case where the clamping device is used, the clamping force specified in the relevant specification shall be applied. The glued, taped or clamped cores shall relax under the specified conditions (see IEC 62044-1:2002, Clause 3) for a long enough time to allow any variation of stress effects, due to clamping, gluing or taping, to become negligible.

4.4 Measuring equipment

4.4.1 Any suitable measuring equipment may be used. Examples of appropriate circuits are given in Annex A to Annex E.

In addition to any requirement specified for the particular method or measuring circuit, or both, used, the following general requirements shall be met.

4.4.2 To ensure the magnetic flux density (field strength) mode of excitation, the output impedance of the exciting source shall be low (high) compared with the series impedance of the exciting winding of the measuring coil assembled with the core under test and the current sensing resistor.

4.4.3 When the sinusoidal waveform of excitation is specified, the total harmonic content of the excitation source shall be less than 1 %. When square pulses are specified, the relevant requirements of Annex F shall be met.

4.4.4 During the period of measurement, the excitation amplitude variations shall not exceed ±0,05 % and the frequency stability shall be adequate for the measuring method and the equipment used.

4.4.5 The frequency range of voltmeters and other voltage sensing instruments shall include all harmonics of the measured voltage having amplitudes of 1 % or more of their fundamentals. This frequency range shall be specified in the relevant instrument specification.

4.4.6 The voltmeters and other voltage sensing instruments used shall be high-impedance instruments, the connection of which will have only a negligible effect on the measuring circuit, especially at high frequencies. The probes of a high-input resistance and a low-input capacitance can reduce the load effects.

4.4.7 The accuracy of the voltmeters or voltage sensing instruments, determined for the calibrating sinusoidal waveform, shall be within ±0,5 % for RMS and average values and ±1 % for peak values, provided that the peak factor of waveforms to be measured is within limits imposed by the instrument.

If inaccuracies exceed the above limits, only a sine-wave excitation of total harmonic content less than 1 % is recommended and

- to determine the RMS, average and peak values of sinusoidal waveforms, a true RMS sensing voltmeter of accuracy within ±1 % is recommended. The average and peak values are obtained by multiplying the indicated RMS values by the following factors: average value = 0,900 × RMS value, peak value = 1,414 × RMS value;
- to determine the RMS, average and peak values of non-sinusoidal waveforms, a digital storage and processing oscilloscope or appropriate acquisition and processing instrument shall be used. It shall be capable of capturing and processing the waveform with the sampling rate not less than 150 samples per waveform period and the resolution not less than 8 bits.

NOTE The peak factor is the ratio of the peak value to the RMS value of the measured waveform.

4.4.8 The resistance of the in-series current sensing resistor shall be known with an inaccuracy not exceeding ±1 digit on the third significant place, including possible thermal variations of the resistance. A heat-sinking or cooled base of the resistor can moderate the above thermal variations.

The inductance L_R of the resistor R over the frequency range specified in 4.4.5 shall not exceed a value

$$L_R \leq \frac{R}{\omega_m}\sqrt{2\delta\hat{U}_R}$$

where

R	is the value of the resistor;
$\omega_m = 2\pi f_m$	f_m being equal to the highest frequency within the frequency range specified in 4.4.5;
$\delta\hat{U}_R$	is the allowable relative increase in the voltage drop $\hat{U}_R$ across the resistor R, due to the inductance L, at frequency f_m.

For example, for $\delta \hat{U}_R = 0{,}1\ \%$, R = 1 Ω and the highest frequency f_m = 500 kHz, the inductance L shall be less than $(2\pi \times 500 \times 10^3)^{-1} \times 1 \times (2 \times 0{,}001)^{0{,}5}$ = 14,2 nH.

The current sensing resistor can be replaced by an appropriately adapted current probe provided that this does not reduce the amplitude and phase accuracy over the frequency range as required in 4.4.5. In addition, the current probe shall be a linear device, i.e. not generating harmonics.

NOTE For the amplitude permeability measurement, it is the amplitude accuracy of the current probe which is mainly concerned.

4.4.9 All the connections between the circuit components shall be as short as possible. In addition, connections, if more than one, giving an additional non-equal phase shift shall be of equal length and of the same type. Any phase shift $\Delta\varphi$ (radian) between the channels designed as equiphase to lead the signals corresponding to the magnetic flux density and field strength over the frequency range defined in 4.4.5 shall not exceed a value

$$\Delta\varphi = \pm \frac{\delta P(\Delta\varphi)}{Q}$$

where

$\delta P(\Delta\varphi)$ is that portion of the total inaccuracy of the power loss measurement which is related to the phase shift $\Delta\varphi$;

$Q = \dfrac{\omega \hat{B}_e \hat{H}_e}{2P_v}$ is the quality factor of the core under test;

$\omega = 2\pi f$ is the angular frequency;

$\hat{B}_e$ and $\hat{H}_e$ are the peak values of the effective magnetic flux density and the effective field strength in the core, respectively;

$P_v = P/V_e$ is the power-loss density; V_e is the effective volume of the core.

If a non-sinusoidal excitation is applied, the phase shifts for the harmonics involved shall be determined. Corresponding to each harmonic frequency, the values of the parameters listed above shall be used in the calculation of each harmonic frequency.

For example, $\delta P(\Delta\varphi)$ shall be within ±1 % and Q = 5 for a given core and measuring conditions. Therefore, $\Delta\varphi$ shall be within ±0,01/5 = ±0,002 radian.

4.4.10 Any contact of any intermediary connectors, joints, switches, multiplexers, etc., which is associated with the voltage or current measuring circuit, shall be able to transmit the voltages involved and the conditioning and measuring currents of values specified in the relevant specification. The contact resistance, phase shift, inductive and capacitive couplings, series impedance and parallel admittance resulting from insertion of the contact shall have only a negligible effect on the results measured over all the measuring conditions involved, including the frequency range as specified in 4.4.5.

4.4.11 Measures or calibration, or both, should be taken to ensure that the resultant inaccuracy of measurement for the amplitude permeability and the power loss over all the measuring conditions does not exceed the inaccuracy specified for the given measuring method and circuit specified.

4.4.12 A temperature-controlled environment shall be provided, capable of maintaining the thermal equilibrium between the core and that environment within specified temperature limits during the conditioning, setting, measurement and reading operations.

5 Specimens

Cores taken from normal production and forming closed magnetic circuits shall be used for the measurement.

6 Measuring procedures

6.1 General procedure

6.1.1 The core to be measured is assembled with the measuring coil in accordance with 4.3.

In the case of ring and toroidal cores, apply winding(s) in accordance with 4.2.1.

6.1.2 The core shall be placed in a temperature-controlled environment in accordance with 4.4.12. All measuring operations such as magnetic conditioning, settings and measurement shall be made after the temperature of the core is attained and maintained within allowed tolerance limits.

6.1.3 The voltages corresponding to the peak value of the magnetic flux density $\hat{B}_e$ and to the peak value of the field strength $\hat{H}_e$ at which the measurement has to be performed are calculated in accordance with the following formulae:

– for $\hat{B}_e$ excitation: $U_{av} = 4 \cdot f \cdot N \cdot A_e \cdot \hat{B}_e$

where N is equal to N_1 when a single winding (both for exciting and voltage sensing functions) is used and N is equal to N_2 when a secondary winding is used for the voltage sensing;

– for $\hat{H}_e$ excitation:

$$\hat{U}_R = \frac{R \cdot l_e \cdot \hat{H}_e}{N_1}$$

where

$\hat{U}_R$ is the peak value of the voltage across the series resistor R;

N_1 is the number of turns of the excitation winding N_1.

The symbols are defined in 3.2, and N_1 is the number of turns of the exciting winding.

NOTE 1 For the practically pure sinusoidal waveform of magnetic flux density $\hat{B}_e$, the voltage, corresponding to $\hat{B}_e$, can be measured using also RMS or peak reading voltmeters or instruments. The respective RMS, U_{rms}, and peak, $\hat{U}$, values of this voltage are calculated as

$$U_{rms} = \sqrt{2} \cdot \pi \cdot f \cdot N \cdot A_e \cdot \hat{B}_e$$

$$\hat{U} = 2 \cdot \pi \cdot f \cdot N \cdot A_e \cdot \hat{B}_e$$

NOTE 2 If the current probe is used instead of the resistor R, the peak value of the current $\hat{I}$ corresponding to $\hat{H}_e$ is calculated as $\hat{I} = \hat{H}_e$.

NOTE 3 If a cross-section area other than A_e is used, for example A_{min}, for the calculation of U_{av}, this will be clearly stated in the relevant specification.

6.1.4 The core is conditioned by the electrical method in accordance with IEC 62044-1:2002, 5.2a), unless otherwise stated.

6.1.5 At the specified time t_c after the start of the conditioning, the exciting source is set, as quickly as possible, preferably within t_c = (2 ± 0,5) s for the time-dependent parameters, to the required frequency, waveform and amplitude of excitation.

To keep the correct excitation waveform within all the measuring conditions, it should be under control. In the case of the magnetic flux density mode of excitation, the input of the control device should preferably be connected to a separate voltage sensing winding.

6.1.6 At the time t_m, the measurement readings shall be taken and then the excitation promptly turned off. The time period when the core is under specified excitation shall be as short as possible but no longer than 10 s, to prevent the core from excessive self-heating.

6.1.7 When a core is excited under pulse conditions with or without a biasing component, the respective complementary specifications of Annex F shall be considered.

6.2 Measuring method for the effective amplitude permeability

6.2.1 Purpose

To provide a method for the measurement of the effective amplitude permeability at high excitation levels and symmetrical periodic waveforms of magnetic cores forming closed magnetic circuits.

NOTE As an alternative, the peak value of the magnetic flux density obtained at the specified peak value of the field strength or, otherwise, the peak value of the field strength at the specified peak value of the magnetic flux density can be determined.

6.2.2 Principle of the measurement

The magnetic flux density and the field strength in a core are determined by measuring the average value of voltage per half-period across the voltage sensing winding of the measuring coil wound on the core and the peak value of the voltage across the resistor in series with the exciting winding of that coil. The measurements are carried out at specified peak values either of magnetic flux density or field strength, frequency and temperature.

6.2.3 Circuit and equipment

Any suitable equipment may be used provided that it is able to fulfil the function of the circuits shown in Annex A.

The requirements of 4.4 shall be met. Since the magnetic flux density and field strength waveforms are not critical in the case of measurement of the amplitude permeability, it will not be necessary to rigorously meet the requirements of 4.4.2 and 4.4.3.

If the amplitude permeability has to be determined for the peak values of fundamental components of the waveforms of the magnetic flux density and field strength, these peak values should be measured by frequency selective instrument(s) observing the requirements of 4.4.

6.2.4 Measuring procedure

The general procedure of 6.1 shall be applied.

For the specified average value U_{av} of the voltage across the voltage sensing winding, either the peak value $\hat{U}_R$ of the voltage across the resistor R or the peak value $\hat{I}$ of the current flowing through the exciting winding is read.

For the field strength excitation, the value of U_{av} is read at the specified value of either $\hat{U}_R$ or $\hat{I}$.

NOTE When the specification requires the magnetic flux density to be measured at the specified field strength or, inversely, the field strength at the specified magnetic flux density, the specified peak value of the excitation is set, and either the resultant $\hat{B}_e$ or the resultant $\hat{H}_e$ is determined, respectively.

6.2.5 Calculation

The effective amplitude permeability is derived from

$$\mu_{ea} = \frac{\hat{B}_e}{\mu_0 \cdot} = \frac{l_e R}{4 \cdot \mu_0 \cdot f \cdot N_1 \cdot N_2 \cdot A_e} \cdot \frac{U_{av}}{\hat{U}_R}$$

or if the current probe is used instead of resistor R

$$\mu_{ea} = \frac{l_e}{4 \cdot \mu_0 \cdot f \cdot N_1 \cdot N_2 \cdot A_e} \cdot \frac{U_{av}}{\hat{I}}$$

where

U_{av} is the average value of voltage across voltage sensing winding N_2;

$\hat{U}_R$ is the peak value of the voltage across the series resistor R;

$\hat{I}$ is the peak value of the current flowing in the excitation winding N_1;

N_1 is the number of turns of the excitation winding N_1;

N_2 is the number of turns of the sensing winding N_2;

the remaining symbols being defined in 3.2.

NOTE If the exciting and voltage sensing functions are performed only by the primary winding N_1, N_2 is replaced by N_1 and the product N_1 N_2 is replaced by N_1^2.

6.3 Measuring methods for the power loss

6.3.1 Purpose

To provide methods for the measurement of power loss at high excitation levels and periodic waveforms in magnetic cores forming closed magnetic circuits.

6.3.2 Methods and principles of the measurements

6.3.2.1 General

The following methods are suitable according to the principle and application.

6.3.2.2 Root-mean-square method (RMS method)

This method is:

- generally applicable provided the circuit components, mounting and equipment used meet the requirements of 4.4;
- less sensitive to distorted waveforms.

The RMS value of the sum and the difference of the two voltages, the first across the unloaded measuring winding of the measuring coil assembled with the core, and the second across the resistor in series with the exciting winding of that coil, are measured by means of the true RMS voltmeter. The difference of the squares of these RMS voltages is proportional to the power loss in the core.

The related measuring procedure is given in Annex B.

6.3.2.3 Multiplying methods

6.3.2.3.1 General

These methods, based on the identical voltage-current multiplying principle, are sensitive to phase-shift errors.

The voltage related to the magnetic flux density and the voltage related to the field strength in the core are acquired, processed and multiplied by either analogue, digital or mixed way in the time or frequency domain techniques. Some of these methods are shown in Table 1.

Table 1 – Some multiplying methods and related domains of excitation waveforms, acquisition, processing

Measuring method	Domain of			Clause of Annex C
	useable excitation waveform	acquisition	processing	
V-A-W meter	Sinusoidal	Time	Time	C.5
Impedance analyzer	Sinusoidal	Not applicable	Not applicable	C.6
Digitizing	Arbitrary	Time	Time	C.7
Vector spectrum	Arbitrary	Frequency	Frequency	C.8
Cross-power	Arbitrary	Time	Frequency	C.9

The related measuring procedures are given in Annex C.

6.3.2.3.2 V-A-W (volt – ampere – watt) meter method

This method is restricted to sinusoidal excitation as defined in 4.4.3.

A V-A-W meter multiplies internally the measured voltages and gives a time average of the product of the instantaneous values of these voltages which is proportional to the power loss of the core.

6.3.2.3.3 Impedance analyzer method

This method is restricted to sinusoidal excitation as defined in 4.4.3.

The impedance analyzer determines at the fundamental frequency the vector components of the voltages related respectively to the magnetic flux density and to the field strength in the core and calculates a parallel resistance related to the power loss in the core. The square of the voltage related to the magnetic flux density divided by the parallel resistance gives the power loss in the core.

6.3.2.3.4 Digitizing method

This method is suitable for arbitrary excitation waveforms.

The measured voltages are sampled and converted into digital data by a digitizer. At each sample point the product of the voltages involved is calculated. The power loss is proportional to the average of the multiplied voltages over one cycle.

6.3.2.3.5 Vector spectrum method

This method is suitable for arbitrary excitation waveforms.

The amplitudes and the phase difference of the voltage signals are measured by a network analyzer. The measurements are made at the fundamental and harmonic frequencies of the applied voltages.

The power loss in the core is obtained by adding up the power-loss components corresponding to the fundamental and harmonic frequencies.

6.3.2.3.6 Cross-power method

This method is suitable for arbitrary excitation waveforms.

At the specified value of excitation, one or more cycles of the measured voltages are sampled and converted into digital data.

The complex spectrum of the measured cycles is computed by fast Fourier transform (FFT). The cross-power spectrum is deduced from these data.

The power loss in the core is obtained by adding up the real parts of the cross-power spectrum at each frequency.

6.3.2.4 Reflection measurement method

This method based on the measurement of the difference between forward power P_F and reflected power P_R is

- not limited to only sinusoidal excitations;
- applicable for frequencies higher than 500 kHz;
- more suitable to the magnetic flux density mode of excitation than the field strength mode of excitation.

The measurement is made using a reflection meter connected to a two-channel measurement head. A voltmeter connected in parallel to the voltage sensing winding monitors the voltage. An average value sensing voltmeter or instrument connected to a voltage sensing winding enables the peak value of the exciting magnetic flux density to be set.

NOTE For the field strength mode of excitation, the insertion of a current sensing series resistor connected in parallel to a voltage measuring instrument can decrease the accuracy of the measurement.

The related measuring procedures are given in Annex D.

6.3.2.5 Calorimetric measurement methods

These methods, based on the measurement of temperature rise of the fluid in the vessel caused by power loss in the wound core, are

- especially suited for calibration purposes;
- less dependent on the measurement frequency;
- not sensitive to distorted waveforms;
- time consuming (typically several hours per measurement point).

In the state of thermal equilibrium, the power loss is determined either by measuring the temperature difference ΔT (induced by power dissipation in the wound core) across a calibrated thermal resistance or by matching this ΔT to an equal value of ΔT induced by the supply of a determinable level of power to a heating (ohmic) resistor.

In the state of non-thermal equilibrium, the desired measured temperature is used as a set point. The determination of power loss in the wound core can be made by supplying determined levels of power through an ohmic resistor with and without the supply of power to the wound core.

The related measuring procedures are given in Annex E.

7 Information to be stated

If the measurements have to be made in accordance with this document, the following information shall be stated:

1) measuring frequency(ies);
2) temperature(s) of the measurement(s) with tolerance(s);
3) mode of excitation: magnetic flux density or field strength;
4) waveform of the excitation;
5) cross-section area of the core used for calculations, if other than the effective cross-section area A_e;
6) peak value(s) of the excitation;
7) measuring method and related measuring circuit;
8) number of turns, N_1, of the exciting winding;
9) number of turns, N_2, of the voltage sensing winding (if used);
10) number of turns, N_3, of the measuring winding if such winding is required;
11) type and size of wires and arrangement of windings on the core;
12) initial amplitude of the electrically conditioning current;
13) time periods at which the excitation is set, t_c, and the measurement made, t_m, after the start of magnetic conditioning;
14) degree of accuracy;
15) results to be presented, for example a single result; a set of single results or functional characteristics, such as power loss as a function of temperature at given values of effective magnetic flux density $\hat{B}_e$ and at a given frequency; or amplitude permeability as a function of effective magnetic flux density at a given frequency and temperature.

When the measuring or test conditions (items 1) to 6)), or both, relevant to core material properties are chosen, the specifications given in IEC 60401-3:2015, Clause 3 and Clause 4, and in IEC 61332:2016, 4.3, should be considered.

NOTE 1 Item 10) is not required with regard to the amplitude permeability measurement.

NOTE 2 If necessary, more information can be required in detailed specifications.

8 Test report

The test report shall contain as necessary:

a) the statement of the test conformity with this document;

b) the type, dimensions, material and serial number or mark of the test specimen(s);

c) the sample size;

d) the parameters measured;

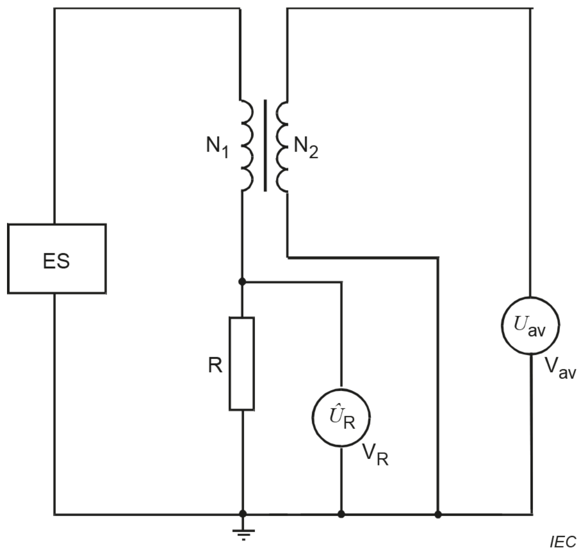
e) the test method used and its accuracy;

f) the test conditions (Clause 7, item 1) to item 6)).

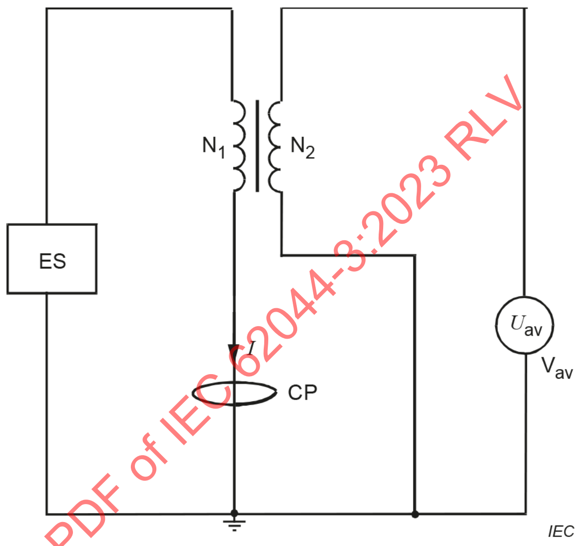
Annex A
(informative)

Basic circuits and related equipment for the measurement of amplitude permeability

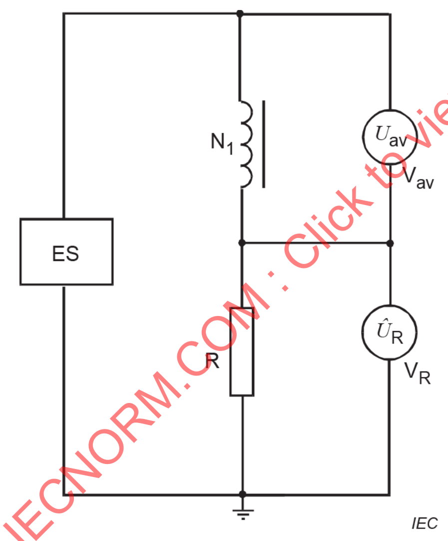
The basic circuits are shown in Figure A.1.



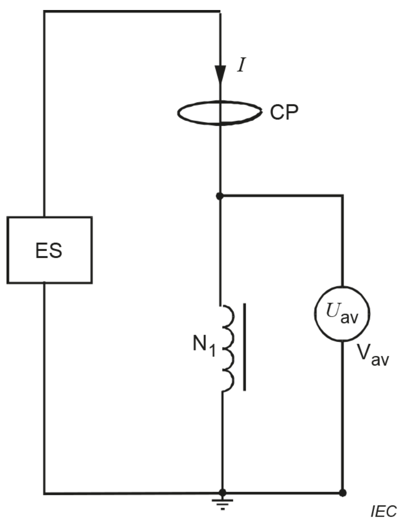
a) Circuit a)



b) Circuit b)



c) Circuit c)



d) Circuit d)

Connections and supplies

Circuit a) two windings, exciting N_1 and voltage sensing N_2, with current sensing non-reactive resistor R;

Circuit b) two windings, exciting N_1 and voltage sensing N_2, with current probe CP;

Circuit c) single exciting winding N_1 with current sensing non-reactive resistor R and floating input instruments V_{av} and V_R;

Circuit d) single exciting windings N_1 with current probe CP.

Components

ES	exciting source containing usually a generator and power amplifier;
R	resistor across which the voltage proportional to the current I flowing in the exciting winding is measured;
CP	current probe sensing the peak value $\hat{I}$ of the current;
V_R	voltmeter or instrument sensing the peak value $\hat{U}_R$ of the voltage across the resistor R;
V_{av}	voltmeter or instrument sensing the average value U_{av} of the voltage;
N_1 and N_2	exciting and voltage sensing windings, respectively.

Figure A.1 – Basic circuits for the measurement of amplitude permeability

The circuits and equipment used shall meet the requirements of 4.4.

The resultant accuracy within ±3 % can be obtained if the requirements of 4.4 are met.

Annex B
(informative)

Root-mean-square method for the measurement of power loss – Example of a circuit and related procedure

B.1 Method of measurement

In the RMS method, a switch S is used to connect the RMS sensing voltmeter or instrument to measure both the sum and the difference of two voltages (see Figure B.1); the short-circuiting connections of the switch shall be as close as possible to the switch and the RMS sensing voltmeter or instrument shall be connected to the switch using a low-noise, single-screened, low-capacitance cable.

It is recommended that the voltage measuring instruments V_{rms} and V_{av} be connected by means of high impedance attenuation probes to minimize a risk of transient over-voltage effects on V_{rms} and V_{av}. These effects can result when the excitation is too abruptly turned or the contact position of the switch S changed, or both.

The requirements of 4.4.2, 4.4.4, 4.4.9 and 4.4.10 shall be met.

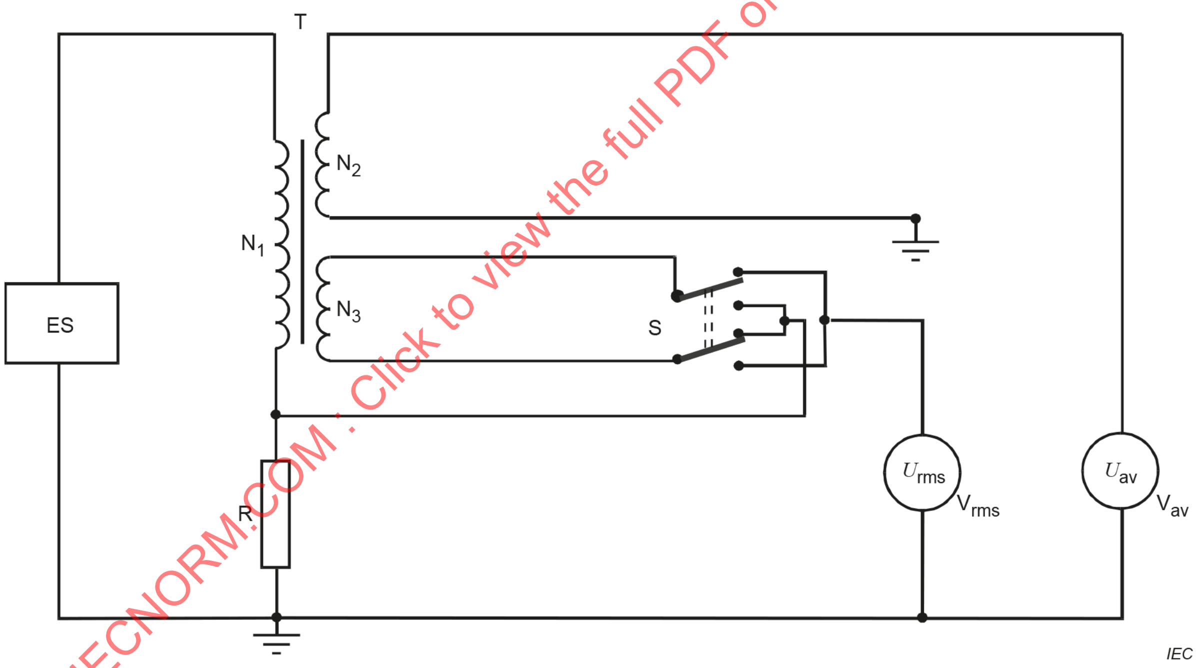


Figure B.1 – Example of a measuring circuit for the RMS method

B.2 Measuring coil

In the RMS method, a triple wound measuring coil with separate exciting winding, measuring winding and voltage sensing winding is used.

NOTE The measuring winding is used to prevent any change of the phase shift between the voltages across the measuring winding and across the resistor R, by any voltage measuring instrument. It also enables the voltmeter to be earthed.

B.3 Measuring equipment

The excitation source ES shall meet the requirements specified in 4.4.3 and 4.4.4. For rectangular voltage pulses, with or without bias, the exciting source shall meet the requirements of Clause F.6. If the core is to be excited by waveforms other than the sinusoidal or rectangular ones, requirements modelled on those of Clause F.6 shall be specified in the relevant specification.

The transformer T is composed of the core under test and three separate windings wound on it, N_1 being the exciting winding, N_2 being the voltage sensing winding and N_3 being the measuring winding. It is advisable to adjust the number of turns of the measuring winding N_3 so that the voltage across it is of the same order as the voltage drop across the current-measuring resistor R. The accuracy of the method increases as these voltages approach numerical equality.

V_{rms} is a true RMS voltmeter or other instrument performing that function. V_{av} is an average value sensing voltmeter or instrument. Both V_{rms} and V_{av} shall meet the requirements of 4.4.5, 4.4.6 and 4.4.7.

Other requirements of 4.4 shall also be met.

B.4 Measuring procedure

The general procedure of 6.1 should be met. In this method, indications of the RMS sensing voltmeter or instrument are read when it is connected to measure first the sum and then the difference of the two voltages. These readings shall be taken, as quickly as possible, so that they are only negligibly influenced by differences in the thermal state of the core and measuring coil.

The calculation is a follows:

The core power loss is given by

$$P = \overline{(u \cdot i)} = \frac{\left|U_1^2 - U_2^2\right|}{4 \cdot \frac{N_3}{N_1} \cdot R}$$

where

$\overline{(u \cdot i)}$ is the time-averaged product of the instantaneous values of the voltage induced by the excitation in the measuring coil assembled with the core and the current through the exciting winding;

U_1 is the RMS value of the sum of the voltages across the measuring winding and across the resistor R;

U_2 is the RMS value of the difference of the above voltages;

N_1 is the number of turns of the exciting winding of the measuring coil;

N_3 is the number of turns of the measuring winding of the measuring coil;

R is the value of the current-measuring resistor.

B.5 Pulse measurement and accuracy

In the case of pulse measurements, the pulse repetition frequency f_p is chosen by consideration of the recovery time. It is therefore preferable, in this case, to express the power loss in terms of energy per cycle, $P = \frac{\overline{(u \cdot i)}}{f_p}$. For a given pulse amplitude and pulse duration, E is independent of f_p and in general, $P = E \cdot f_p$.

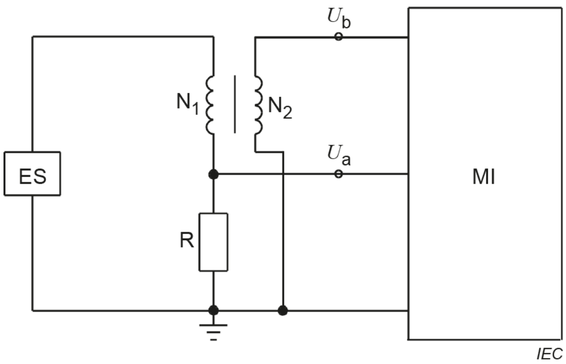
For this method, the resultant accuracy within ±5 % can be obtained for the power loss determination if the requirements of 4.4 are met.

Annex C
(informative)

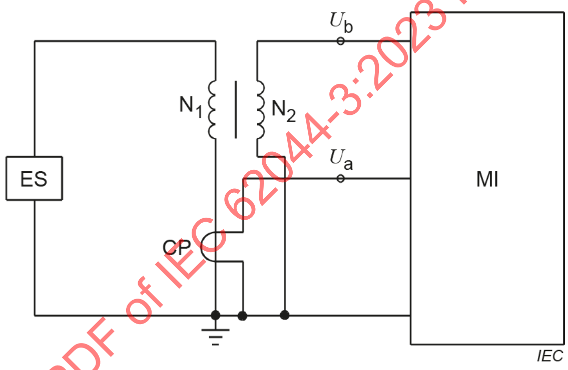
Multiplying methods for the measurement of power loss – Basic circuits and related measurement procedures

C.1 Basic circuits

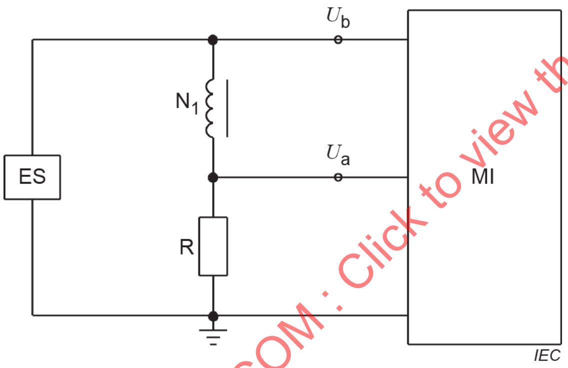
The basic circuits are shown in Figure C.1.



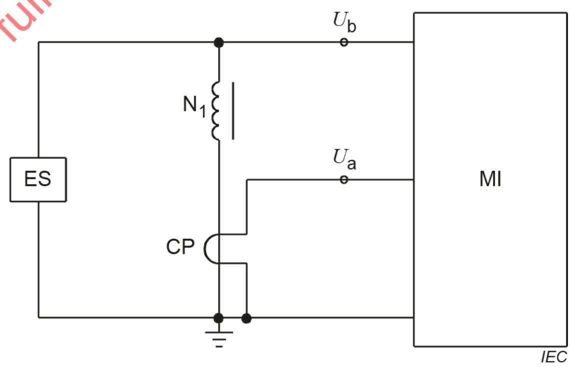
a) Circuit a)



b) Circuit b)



c) Circuit c)



d) Circuit d)

Connections and supplies

Circuit a)	two windings, excitation N_1 and voltage sensing N_2 with current sensing non-reactive resistor R;
Circuit b)	two windings, exciting N_1 and voltage sensing N_2 with current probe CP;
Circuit c)	single excitation winding N_1 with current sensing non-reactive resistor R and floating inputs;
Circuit d)	single excitation winding N_1 with current probe CP.

Components

ES	excitation source;
R	non-reactive current sensing resistor across which the voltage U_a, proportional to the current I flowing through the exciting winding N_1, is measured;
MI	measuring instrument which fulfills the function of acquiring and processing, including the multiplication of the voltages U_a and U_b;
N_1	excitation winding;
N_2	voltage sensing winding;

U_a voltage drop proportional to the current I flowing through the exciting winding;

U_b voltage drop across either the N_1 or N_2 winding; the average value of U_b is proportional to the magnetic flux density in the core (see 4.2.2);

U_a and U_b symbolize the instantaneous, average or RMS values of the voltages, depending on the specific multiplying method.

The exciting source ES normally includes the generator and power amplifier; an impedance matching adapter can also be added. Exciting source ES and measuring instrument MI can be integrated into one, often computer controlled, measuring unit (system).

The current probe CP, if used, should be a linear device, i.e. that will not generate harmonics and shall comply with the requirements of 4.4.8.

Figure C.1 – Basic circuits for multiplying methods

C.2 Requirements

The circuits and measuring equipment used shall meet the requirements of 4.4.

C.3 Measuring coil

The requirements of 4.2 shall be met.

C.4 Accuracy

The ultimate accuracy of the test equipment is a complex function dependent upon measuring instruments and other characteristics of the measuring conditions and equipment; it is therefore not always possible to state the absolute accuracy that is attainable by a given multiplying instrument of a system at all measuring conditions.

Amplitude and phase measurement errors influencing strongly the accuracy of the power loss measurement can be a combination of factors related to the following errors:

- residual errors after calibration;
- errors of calibration standard;
- tracking error between two measurement channels (amplitude and phase);
- non-linearity of the instrument (for example, amplifier, mixer, A-D converter, current transformer);
- frequency error;
- accuracy of settings (for example, of flux density);
- calculation errors.

Reference should be made to the manufacturer's instructions accompanying the instrument for guidance on errors that can occur and their correction, particularly with respect to circuit connections and the calibration procedure.

To minimize the errors, the requirements of Clause 4 shall be conscientiously observed and harmonized with the multiplying instrument capabilities and with the error limits corresponding to particular measuring ranges of the instrument.

C.5 V-A-W (volt-ampere-watt) meter method

The measured voltages are multiplied internally in the V-A-W meter. The V-A-W meter determines the time average of the product of the voltages which is proportional to the power loss in the core, P.

The calculation is as follows:

The power loss in watts (W) is given by the following formula:

$$P = (\overline{u \cdot i}) = \mathrm{K} \cdot \alpha$$

where

$(\overline{u \cdot i})$ is the time average of the instantaneous values of the power loss in the core;

α is the reading of the V-A-W meter;

K is the instrument constant.

C.6 Impedance analyzer method

The impedance analyzer determines the vector components of the measured voltages and calculates the equivalent parallel resistance R_p.

The calculation is as follows:

The measured power loss P in watts (W) is given by

$$P = \frac{U_\mathrm{rms}^2}{R_\mathrm{p}}$$

where

U_rms is the RMS value of the measured voltage across the exciting winding.

NOTE Although the measured power loss is calculated via the equivalent parallel resistance R_p, the calculation of this loss can also be related to a direct multiplication of the current and voltage signals. Therefore the measured power loss P which is equal to $U_\mathrm{rms}{}^2/R_\mathrm{p}$ can also be expressed as

$$P = U_\mathrm{rms} \cdot I_\mathrm{rms} \cdot \cos \varphi.$$

C.7 Digitizing method

The voltages $u_\mathrm{a}(t)$ and $u_\mathrm{b}(t)$, according to Figure C.1, are sampled into values U_{a_i} and U_{b_i} by a digitizer, where i refers to the i^th sample of the signal (i = 1, 2, 3, ...).

The instantaneous power loss values at each sample point i within the sample cycle is proportional to the product $U_{\mathrm{a}_i} \cdot U_{\mathrm{b}_i}$.

The calculation is as follows:

With n samples for the measuring cycle the measured power loss is calculated by

$$P = \alpha \cdot \frac{1}{n} \cdot \sum_{i=1}^{n} (U_{ai} \cdot U_{bi})$$

where

α is the constant of proportionality, depending on the circuit arrangement.

C.8 Vector spectrum method

The network analyzer measures the RMS values of the fundamental and harmonic voltages U_{ak} and U_{bk} together with the phase angle ϕ_k between these voltages, where k is the k^{th} harmonic number (k = 1,2,3,..).

Calculation

The measured power loss P is given by

$$P = \alpha \cdot \sum_{k} (U_{ak} \cdot U_{bk}) \cdot \cos \varphi_k$$

where

α is the constant of proportionality, depending on the circuit arrangement.

C.9 Cross-power method

The sampling of the voltage is performed as described in the digitizing method. The voltages $\mu_a(t)$ and $\mu_b(t)$ are processed by FFT (fast Fourier transform) in order to obtain the RMS values of the fundamental and harmonic voltages: U_{ak} and U_{bk}, together with the phase angle ϕ_k between these two voltages.

The calculation is as follows:

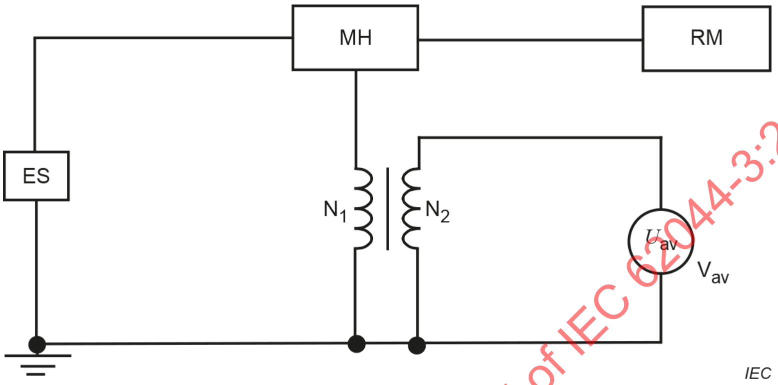
The calculation of the measured power loss is the same as for the vector spectrum method.

Annex D
(informative)

Reflection method for the measurement of power loss – Basic circuit and related measurement procedures

D.1 Basic circuit

The basic circuit is shown in Figure D.1.



Components

ES exciting source containing usually a generator and power amplifier;

RM reflection meter;

MH two-channel measurement head;

V_{av} voltmeter or instrument sensing the average value of the voltage U_{av}.

Figure D.1 – Basic circuit

D.2 Requirements

The circuits and measuring equipment shall meet the requirements of 4.4. If a non-sinusoidal excitation is applied, the reflection meter shall be able to measure the components of the reflected power averaging not less than seven harmonics.

D.3 Measuring coil

The requirements of 4.2 shall be met.

D.4 Measuring procedure and accuracy

The general procedure of 6.1 should be met. The forward and reflected power are read directly from the reflection meter.

The calculation is as follows:

The measured core power loss is given by

$$P = P_F - P_R$$

where

P_F is the forward power;

P_R is the reflected power.

The measurement accuracy depends on such main error factors as

- instrument errors;
- impedance mismatch.

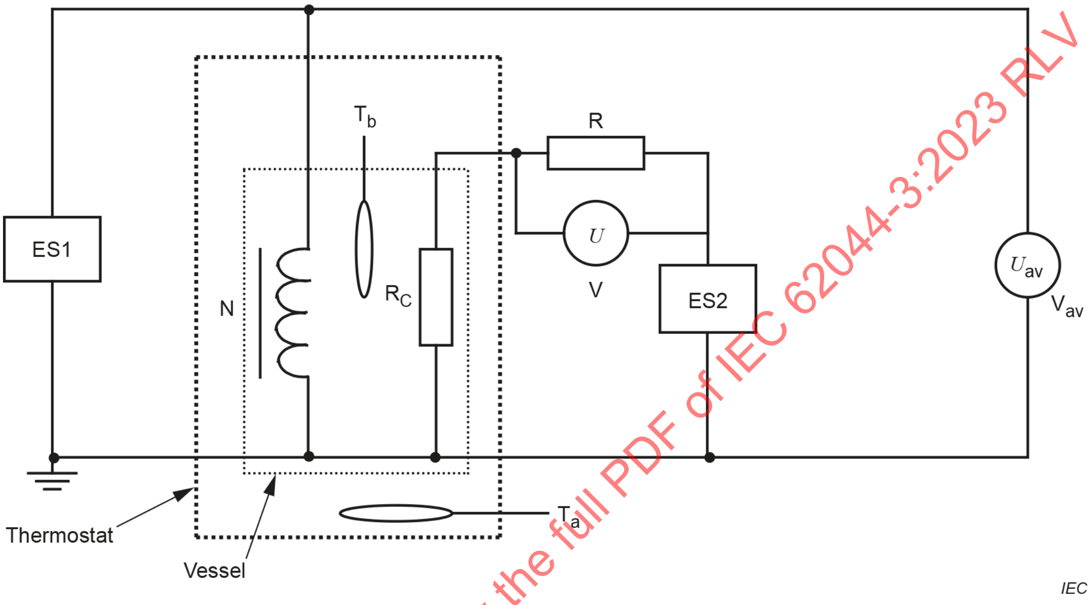
To minimize errors the requirements of Clause 4 shall be conscientiously followed. The measurement accuracy is decreased as the subtraction result $P_F - P_R$ is decreased.

Annex E
(informative)

Calorimetric measurement methods for the measurement of power loss

E.1 Basic circuit

The basic circuit is shown in Figure E.1.



Components

ES1 excitation source for the measuring coil usually containing a generator and power amplifier;

ES2 excitation source for the heating resistor R_c usually containing a DC generator and power amplifier;

R non-reactive current sensing resistor across which the voltage U, proportional to the current I, is measured;

R_c heating resistor causing a temperature rise of the fluid in the vessel due to the dissipation of a determinable level of power;

N measuring coil;

V_{av} voltmeter or instrument sensing the average value of the voltage U_{av} across the measuring coil;

V voltmeter or instrument sensing the value of the voltage U across R;

T_a thermostat temperature sensor indicating the thermostat temperature T_a;

T_b vessel temperature sensor indicating the vessel temperature T_b.

T_a shall be kept stable, i.e. independent of ambient temperature, during the measurement.

In order to have T_b as close as possible to the temperature of the wound core, it is recommended that a stirrer be used to achieve a homogeneous temperature distribution.

The fluid in the vessel shall have a small thermal capacity and a high enough boiling temperature.

The fluid in the vessel should have a low permittivity and low dielectric loss at measuring frequency(ies) and temperature(s).

Figure E.1 – Basic circuit and related measurement procedures – Measurement set-up

E.2 Requirements

The circuit and measuring equipment shall meet the requirements of 4.4.

E.3 Measuring coil

The general requirements of 4.2 shall be met.

E.4 Accuracy

For this method the resultant accuracy of ±5 % can be obtained for power loss determination if the specifications in Figure E.1 are observed and the requirements of 4.4 met.

Temperature measurements should be as precise as possible because errors in the temperature measurements strongly influence the accuracy of the power loss measurement.

E.5 Measurements at thermal equilibrium

E.5.1 General

Measurements of the temperature differences (T_a – T_b) are made in a state of thermal equilibrium.

As the final temperature difference, induced either by power dissipation in the ohmic resistor or wound core, settles as a non-linear function of time (due to the combination of thermal resistances and thermal capacitances in the caloric measuring system), its measurement can only be made in a state of thermal equilibrium.

The measuring temperature to determine the core losses is not exactly known in advance because the final temperature difference induced by the power loss in the measuring coil is not known in advance.

NOTE If the temperature difference (T_a – T_b) tends exponentially with time to a constant value, then the influence of the thermal resistances and capacitances can be represented as an effect caused by a combination of one single (thermal) resistance and (thermal) capacity. For this situation, The temperature difference does not need to be measured only at thermal equilibrium. Measurements can be made at an earlier stage because the curve fitting of this response can be used to estimate the final temperatures of thermal equilibrium.

E.5.2 Measurement across calibrated thermal resistance

The thermal resistance R_{th} between the fluid inside the vessel and the thermostat shall be calibrated prior to the power loss measurement and is given by

$$R_{th} = \frac{\Delta T_c}{P_c}$$

where

ΔT_c is the temperature difference between vessel and thermostat given by (T_a – T_b) caused by the power loss in the heating resistor R_c;

P_c is the supplied power through the heating resistor given by $I^2 R_c$.

The power loss in the wound core can be determined by

$$P = \frac{\Delta T}{R_{th}}$$

where

ΔT is the temperature difference between vessel and thermostat given by ($T_a - T_b$) caused by the power loss in the wound core;

R_{th} is the previously calibrated thermal resistance.

E.5.3 Measurement by matching the temperature rise in the core and resistor

Since the calibration of the thermal resistance is time-consuming, an alternative method consists of matching ΔT_c to ΔT by adjusting P_c.

The final temperature rise ΔT due to the core loss in the wound core is measured. Subsequently, this value is used as a set point for the final temperature rise ΔT_c due to the supplied power through the heating resistor.

E.6 Measurements at non-thermal equilibrium

The desired measuring temperature is used as a set point. This set point temperature inside the vessel can be caused by:

a) power loss in the heating resistor only (P_{c1});

b) power loss in the heating resistor and the excited core (P_{c2}).

By measuring the two levels of supplied power to the heating resistor one can obtain the power loss in the wound core (P) by

$$P = P_{c2} - P_{c1}$$

Annex F
(normative)

Magnetic properties under pulse condition

F.1 Object

To provide measuring methods for the core properties which are of importance when using cores under pulse conditions, namely: the pulse inductance factor, or pulse permeability, and the non-linearity of the magnetizing current associated with a specified voltage-time product limit.

F.2 Measurement methods

Refer to 3.1.9 to 3.1.17 for definitions of the terms relating to the measurement methods.

F.3 Principle of the methods

The core is excited by applying square voltage pulses. Two principal methods are possible:

1) The pulses are repeated with a suitable repetition frequency. The voltage across the measuring coil is rectified to eliminate the back swing and measured with an average responding voltmeter. The peak magnetizing current is also measured.
2) Both the curve of the magnetizing current as a function of time $i_m (t)$, and the loop of the voltage across the inductor integrated with respect to time as a function of the magnetizing current $\int u dt$ versus i_m, are displayed on a properly calibrated oscilloscope. This method may be used for both repeated and single pulses, the display being photographed in the latter case.

The pulse inductance factor or the pulse permeability can be determined by either method; the non-linearity of the magnetizing current associated with a specified voltage-time product limit can only be determined by the second method.

F.4 Specimens

Cores taken from normal production, and forming complete magnetic circuits, shall be used for the measurement.

F.5 Measuring coil

The number of turns should be specified in relation to the measuring conditions, the equipment used and the accuracy to be obtained. The resistance and the self-capacitance of the measuring coil at the measuring frequency should be as low as is necessary to make the error negligible. The measuring coil should be situated as closely as possible to, and uniformly along, the part or parts of the core as specified, the winding arrangement normally approximating to that used with the core in its application. In the case of a toroidal core, the turns shall be evenly distributed along the circumference.

When it is impossible to make the coil resistance small enough for the applied voltage to approximate to the e.m.f. with sufficient accuracy, then a double winding measuring coil consisting of a voltage winding and a current winding should be used. The voltage winding should have a resistance very much smaller than the impedance of the attached voltmeter and its self-capacitance should be so small that the error it causes is negligible. It should be wound as close to the core as possible and the current winding shall completely cover the voltage winding.

NOTE 1 An electrostatic screen between the two windings can be desirable.

NOTE 2 When winding a coil onto a sharp-edged core, the wire insulation will not be able to rupture.

F.6 Measuring equipment

Any suitable measuring equipment can be used. Examples of appropriate circuits for measurement with exponential recovery are given in Annex G. The following requirements shall be met:

a) Pulse generator

When connected to the coil, the test circuit being adjusted for the appropriate back swing and recovery time, the pulse generator used for these measurements shall supply voltage pulses of the required amplitude, duration and repetition rate and meet the following general requirements:

1) when adjusted to a given value, the pulse amplitude shall remain constant within 5 %;
2) the power available from the source shall be sufficient to obtain a voltage pulse having a droop not exceeding 10 %;
3) the switching shall be fast enough not to affect the rise time and the fall time significantly;
4) the overshoot shall not exceed the specified limits.

b) Current measurement

The current through the measuring coil (or its current winding) shall be measured by means of either:

1) a current probe which yields a signal proportional to the current within 2 % and which, when connected to the oscilloscope, does not adversely affect the voltage pulse droop; or
2) a precision resistor between the test coil and earth which causes a voltage drop not exceeding 1 % of the nominal pulse amplitude and has negligible inductance.

c) Recovery time

For measurement with repeated pulses, the time constant of the measuring circuit shall be such that the recovery time is smaller than the interval between the pulses in order to ensure that the flux in the core returns to its initial value.

d) Voltmeter

When using the average voltmeter method, the voltmeter shall be a Class 1[1] instrument or better and the diode shall be so chosen that it introduces negligible error.

1 Class index: see IEC 60051-1.

e) Oscilloscope method

When the oscilloscope method is used, the time constant of the voltage integrating circuit shall exceed 100 times the pulse duration or 100 times the effective time constant of the recovery, whichever is the greater, and its phase shift should be as small as possible.

Calibration facilities shall be provided for the display of voltage and current to obtain an overall accuracy of the measured pulse inductance factor better than 5 %.

The connecting cables to the oscilloscope shall be of a low capacitance type (e.g. air insulated cables).

F.7 Measuring procedure

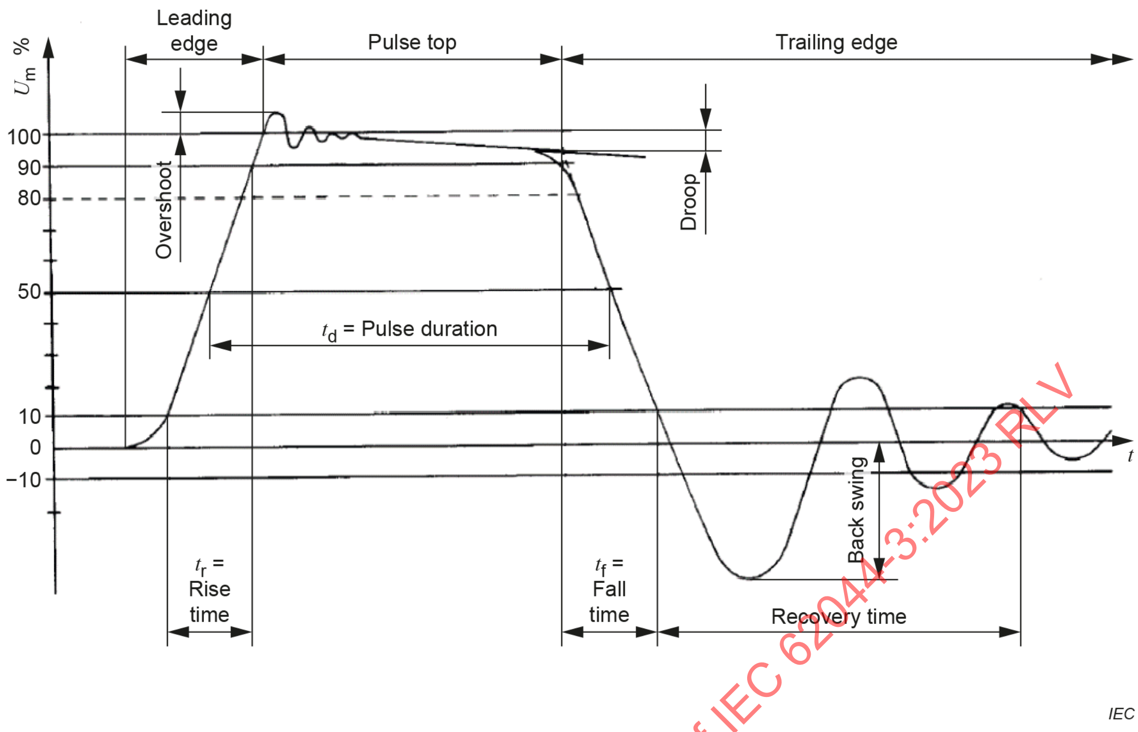
F.7.1 General

a) The core to be measured is assembled with the measuring coil in accordance with 4.2.1 and 4.3.

b) For measurement with repeated pulses, the pulse repetition rate is so chosen that the self-heating of the coil and the core is negligible.

c) The generator is checked to ensure that it will meet the specified voltage pulse characteristics, the measuring coil being replaced by a resistor which has a resistance approximately equal to the absolute value of the coil impedance under pulse conditions. Figure F.1 shows a pulse with exaggerated distortion for the purpose of defining the relevant parameters.

In the pulse as displayed on the oscillograph, a straight line shall be drawn exactly coinciding with the steady voltage between pulses, and a straight line or a simple curve of the exponential type coinciding with most of the pulse top. The intersection of this latter line with the actual pulse leading edge gives the pulse amplitude U_m. Lines are drawn parallel to the time axis at -10 %, +10 %, +50 %, +80 % and +90 % of U_m. A straight line is drawn through the points where the pulse reaches 0,9 U_m for the last time and next reaches 0,1 U_m; when the droop is nearly 10 % of U_m, however, the value of 0,8 U_m shall be used instead of 0,9 U_m. The intersection of this line with that drawn on the pulse top is the border between pulse top and trailing edge.



NOTE For clarity in illustrating the droop, the 80 % and 10 % points have been used in constructing the line which determines the border between the pulse top and the trailing edge.

Figure F.1 – Voltage pulse parameters

F.7.2 Measurement of pulse inductance factor and magnetizing current

a) For measurement without bias, a measuring coil conforming with Clause F.5 shall be used. For measurement with bias, an additional bias winding having a specified number of turns shall be wound over the measuring coil, and connected to a DC power supply through an impedance of such magnitude that the bias winding has no appreciable effect on the value of the current through the measuring coil.

When making measurements with a biasing field, the direct current I_b in the bias winding is adjusted to correspond to the specified value of the biasing field strength H_b:

$$I_b = \frac{H_b \cdot l_e}{N_b}$$

where:

l_e is the effective magnetic path length of the core;

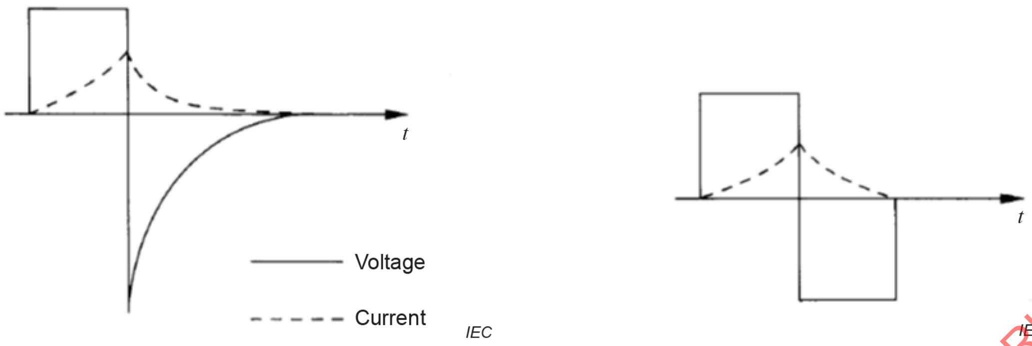
N_b is the number of turns of the bias winding of the measuring coil.

NOTE 1 Reference is often made to the biasing ampere-turns:

$$I_b N_b = H_b \cdot l_e$$

b) The measuring circuit is adjusted to give the specified voltage pulse characteristics including pulse duration and recovery time.

NOTE 2 With the coil connected in the measuring circuit, the voltage pulse waveform for exponential and linear recovery will appear typically as in Figure F.2.



a) **Exponential recovery** b) **Linear recovery**

Figure F.2 – Typical measuring waveforms

The applied pulse voltage amplitude is then increased, maintaining the specified pulse characteristics, to give a reading on the average reading voltmeter or on the oscilloscope corresponding to the specified flux change $\Delta\Phi$ in the core as indicated below:

– for measurements with repeated pulses $u_{av} = N \cdot \Delta\Phi \, f_p$.

– for measurements with isolated pulses $\int u\,dt = N \cdot \Delta\Phi$

where:

N is number of turns of the measuring coil winding connected to the voltmeter or oscilloscope;

f_p is the pulse repetition rate.

For measurements with repeated pulses the pulse shape and repetition frequency are checked and adjusted when necessary, and the average voltage u_{av} and the peak magnetizing current $\hat{i}_m$ are recorded.

For measurements with isolated pulses the displayed loop of $\int u\,dt$ versus i_m is photographed, if possible in such a way that the calibration voltage pulses in both co-ordinates are included, and the total excursion of $\int u\,dt$ and the corresponding variation of magnetizing current are recorded.

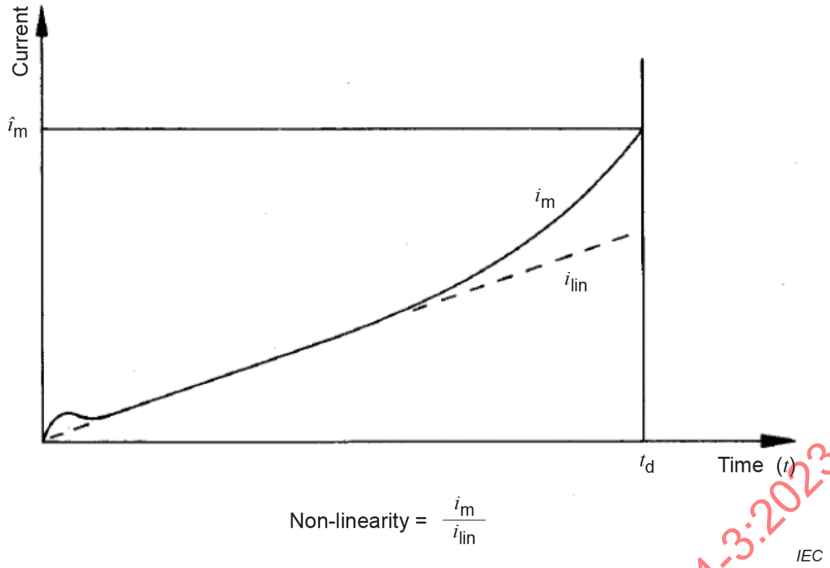
NOTE 3 A better accuracy can be obtained when use is made of a digital processing method.

F.7.3 Measurement of the non-linearity of the magnetizing current

This measurement is made to determine that the claimed value of non-linearity of the magnetizing current is not exceeded at the specified voltage-time product limit.

NOTE Typical values of non-linearity lie between 1 and 1,5.

Voltage pulses, repeated or isolated, are applied to the measuring coil as in F.7.2. The magnetizing current is displayed on an oscilloscope as a function of time, the display being photographed if necessary. The voltage pulse amplitude is varied until its voltage-time product equals the specified limit value and the non-linearity of the magnetizing current at the end of the pulse is determined (see Figure F.3).



See 3.1.16.

Figure F.3 – Non-linearity of magnetizing current

F.8 Calculation

a) Pulse inductance factor

The pulse inductance factor is calculated from one of the following expressions:

$$A_{LP} = \frac{u_{av}}{f_p \cdot \hat{\imath}_m \cdot N^2} \text{ or } A_{LP} = \frac{\int u dt}{\hat{\imath}_m \cdot N^2}$$

where:

$\int udt$ is the voltage across the measuring coil integrated over the pulse duration (i.e. the total excursion);

u_{av} is the average (half-wave) rectified voltage across the measuring coil;

f_p is the pulse repetition frequency;

$\hat{\imath}_m$ is the peak value of the magnetizing current;

N is the number of turns of the measuring coil winding connected to the voltmeter or oscilloscope.

b) Non-linearity of magnetizing current

In the graph of the magnetizing current as a function of time, recorded as described in F.7.3, the linear portion of the curve is extrapolated. In Figure F.3 the curve labelled i_m shows the original graph and the line labelled i_{lin} shows the extrapolated linear portion of it.

The non-linearity of the magnetizing current, defined as $\frac{i_m}{i_{lin}}$ when measured at time t_d shall not exceed the specified value, corresponding to the specified voltage-time product limit, which for the conditions of measurement described in F.7.3 is given by:

$$(U \cdot t)_{lim} = U_m \cdot t_d$$

c) Pulse inductance factor at voltage-time product limit

The pulse inductance factor corresponding to the specified value of the voltage-time product limit is calculated from the expression:

$$A_{LP} = \frac{(U \cdot t)_{lim}}{\hat{i}_m \cdot N^2} = \frac{U_m \cdot t_d}{\hat{i}_m \cdot N^2}$$

where the symbols have the meanings given in a) and the values of $\hat{i}_m$ and U_m are those corresponding to the method of F.7.3.

Annex G
(informative)

Examples of circuits for pulse measurements

The circuit to be chosen depends upon the conditions to be realized:

- measurement with or without bias;
- measurement with isolated pulses or with repeated pulses.

Figure G.1 shows a circuit suitable for measurement without bias and for isolated pulses; Figure G.2 shows a circuit suitable for measurement with bias and for repeated pulses. The circuits for measurement with bias and isolated pulses, and for measurement without bias and repeated pulses can easily be developed from these examples.

In the case of measurement with repeated pulses, a resistor should be added in parallel with the measuring coil as in Figure G.2. This load resistor R_L has been shown in series with a diode which blocks the current through it during the pulse duration period, in order to conserve power and to avoid excessive dissipation. The value of R_L should be high enough to obtain a recovery time smaller than the interval between the pulses, but not so high that the back swing is excessive.

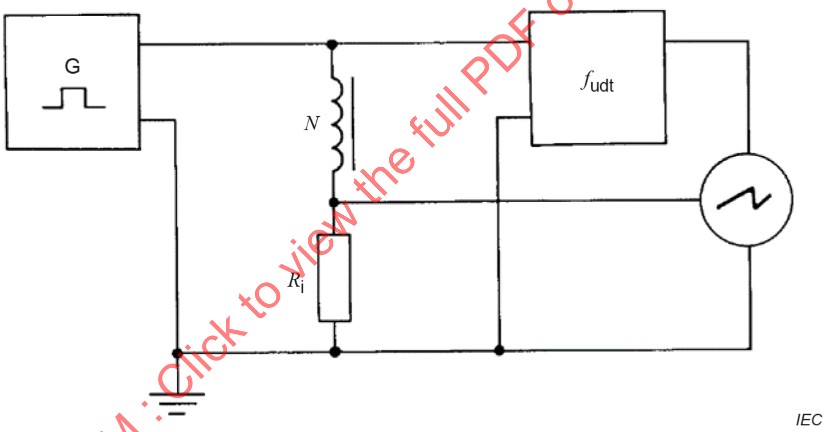


Figure G.1 – Measurement without bias and with single pulses

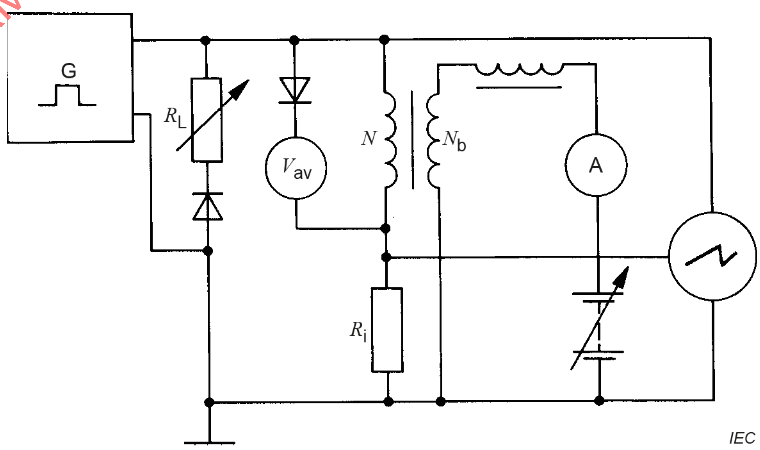


Figure G.2 – Measurement with bias and with repeated pulses

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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NOYAUX EN MATÉRIAUX MAGNÉTIQUES DOUX – MÉTHODES DE MESURE –

Partie 3: Propriétés magnétiques à niveau élevé d'excitation

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Cette deuxième édition annule et remplace la première édition parue en 2000. Cette édition constitue une révision technique.

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

a) ajout de l'Annexe F et de l'Annexe G.

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

Projet	Rapport de vote
51/1426/CDV	51/1439/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.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2, il a été développé selon les Directives ISO/IEC, Partie 1 et les Directives ISO/IEC, Supplément IEC, disponibles sous www.iec.ch/members_experts/refdocs. Les principaux types de documents développés par l'IEC sont décrits plus en détail sous www.iec.ch/publications.

Une liste de toutes les parties de la série IEC 62044, publiées sous le titre général *Noyaux en matériaux magnétiques doux – Méthodes de mesure*, se trouve sur le site web de l'IEC.

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

INTRODUCTION

L'IEC 62044, publiée sous le titre général *Noyaux en matériaux magnétiques doux – Méthodes de mesure*, comprend les parties suivantes:

IEC 62044-1: Spécification générique

IEC 62044-2: Propriétés magnétiques à niveau d'excitation faible

IEC 62044-3: Propriétés magnétiques à niveau élevé d'excitation

NOYAUX EN MATÉRIAUX MAGNÉTIQUES DOUX – MÉTHODES DE MESURE –

Partie 3: Propriétés magnétiques à niveau élevé d'excitation

1 Domaine d'application

La présente partie de l'IEC 62044 spécifie les méthodes de mesure de la perte de puissance et de la perméabilité d'amplitude des noyaux magnétiques qui forment les circuits magnétiques fermés destinés à être utilisés à des niveaux élevés d'excitation dans les bobines d'inductance, les bobines d'arrêt, les transformateurs et les dispositifs similaires pour les applications d'électronique de puissance.

Les méthodes contenues dans le présent document peuvent couvrir les mesures des propriétés magnétiques pour des fréquences qui s'étendent dans la pratique du courant continu à 10 MHz, voire éventuellement au-dessus, pour les méthodes calorimétrique et par réflexion. L'applicabilité des différentes méthodes à des plages de fréquences spécifiques dépend du niveau d'exactitude à obtenir.

Les méthodes du présent document sont fondamentalement les mieux adaptées aux excitations sinusoïdales. D'autres formes d'onde périodiques peuvent également être utilisées; cependant, une exactitude appropriée peut être obtenue seulement si les circuits et les instruments de mesure utilisés sont capables de prendre en compte et de traiter les amplitudes et les phases des signaux concernés dans le spectre de fréquences qui correspond à l'induction magnétique indiquée et aux formes d'onde de champ magnétique avec une exactitude à peine dégradée.

NOTE Pour certains matériaux métalliques magnétiques doux, il peut être nécessaire de suivre des principes généraux spécifiques et normaux pour ces matériaux, liés à la préparation des éprouvettes et des calculs spécifiés. Ces principes sont énoncés dans l'IEC 60404-8-6.

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 62044-1:2002, *Noyaux en matériaux magnétiques doux – Méthodes de mesure – Partie 1: Spécification générique*

3 Termes, définitions et symboles

3.1 Termes et définitions

Pour les besoins du présent document, les termes et définitions suivants s'appliquent.

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

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

3.1.1
perméabilité d'amplitude effective
μ_{ea}
perméabilité magnétique obtenue à partir de la valeur de crête de l'induction magnétique effective, $\hat{B}_e$, et de la valeur de crête du champ magnétique effectif, $\hat{H}_e$, pour des valeurs données de l'une ou de l'autre valeur, lorsque l'induction magnétique et le champ magnétique varient périodiquement en fonction du temps avec une valeur moyenne nulle, le matériau étant initialement dans un état désaimanté spécifié

3.1.2
perméabilité d'amplitude effective maximale
$\mu_{ea\ max}$
valeur maximale de la perméabilité d'amplitude effective lors de variations de l'amplitude d'excitation ($\hat{B}_e$ ou $\hat{H}_e$)

3.1.3
excitation
soit l'induction magnétique soit le champ magnétique pour lequel la forme d'onde et l'amplitude restent toutes les deux dans les limites de la tolérance spécifiée

Note 1 à l'article: Lorsque le mode d'excitation par induction magnétique (par champ magnétique) est choisi, la forme d'onde qui résulte du champ magnétique (de l'induction magnétique) peut être déformée par rapport à la forme d'onde d'excitation en raison du comportement non linéaire du matériau magnétique.

3.1.4
niveau élevé d'excitation
excitations pour lesquelles la perméabilité dépend de l'amplitude d'excitation (en particulier en basse fréquence) ou auxquelles la perte de puissance donne lieu à une augmentation visible de la température (en particulier en haute fréquence), ou les deux

3.1.5
enroulement d'excitation
enroulement de la bobine de mesure auquel est appliquée la tension d'excitation ou à travers lequel s'écoule le courant d'excitation

3.1.6
enroulement de détection de tension
enroulement non chargé d'une bobine de mesure à travers lequel la force électromotrice induite par l'excitation peut être déterminée

3.1.7
enroulement de mesure
enroulement, normalement secondaire, chargé ou non, qui peut être utilisé pour la mesure hors enroulement d'excitation ou enroulement de détection de tension, ou les deux

3.1.8
perte de puissance
puissance absorbée par le noyau

3.1.9
excitation par impulsions sans champ de polarisation
excitation dans laquelle un noyau est alimenté par une impulsion de tension, d'une induction rémanente à une valeur d'induction plus élevée dans la même direction, et dans laquelle le noyau retrouve la même induction rémanente

Note 1 à l'article: La déviation dans le plan B-H associée à une telle impulsion est représentée à la Figure 1.

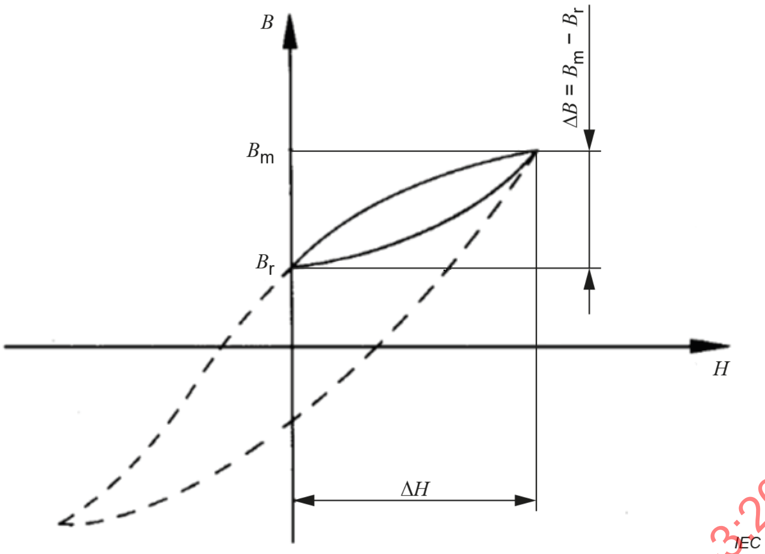

Figure 1 – Excitation par impulsions sans champ de polarisation

Note 2 à l'article: Si la force contre-électromotrice durant la reprise n'est limitée que par la constante de temps du circuit d'essai, alors le courant magnétisant diminue de façon exponentielle.

En variante, la force contre-électromotrice peut être limitée à une valeur constante, par exemple en renvoyant l'énergie par un enroulement secondaire à une source de tension; la diminution du courant magnétisant est alors approximativement linéaire. Cette dernière méthode peut empêcher une force contre-électromotrice excessivement élevée et des taux élevés de variation de flux. La distinction est principalement pertinente pour le mesurage des pertes.

3.1.10
excitation par impulsions avec champ de polarisation
excitation dans laquelle un noyau est alimenté par une impulsion de tension, d'une valeur d'induction déterminée par un champ de polarisation à une induction dans la direction opposée, et dans laquelle le noyau retrouve la même valeur déterminée par le champ de polarisation

Note 1 à l'article: La déviation dans le plan B-H associée à une telle impulsion est représentée à la Figure 2.

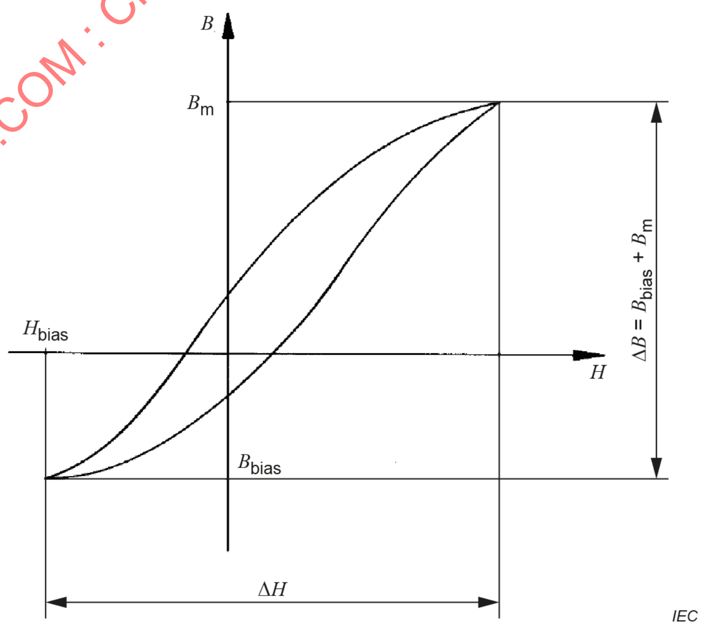

Figure 2 – Excitation par impulsions avec champ de polarisation

Note 2 à l'article: Voir la Note 2 à l'article du 3.1.9.

3.1.11
perméabilité de l'impulsion
μ_p
perméabilité relative obtenue à partir de la variation de l'induction et de la variation correspondante du champ magnétique lorsque l'une ou l'autre des grandeurs varie de façon arbitraire entre des limites spécifiées:

$$\mu_p = \frac{1}{\mu_0} \cdot \frac{\Delta B}{\Delta H}$$

VOIR: Figure 1 et Figure 2.

Note 1 à l'article: La valeur de la perméabilité de l'impulsion dépend fortement des limites des déviations d'induction ou de champ magnétique; il n'est pas nécessaire que ces limites soient symétriques par rapport à la valeur zéro.

Note 2 à l'article: Souvent, la perméabilité de l'impulsion se réfère au cas particulier d'impulsions de tension carrées appliquées à un enroulement d'excitation; la forme d'onde de l'induction magnétique est alors approximativement triangulaire.

3.1.12
amplitude de l'impulsion
U_m
valeur instantanée maximale d'une impulsion de tension idéale par rapport à la valeur stable de la tension entre les impulsions

Note 1 à l'article: Une impulsion idéale est déduite d'une impulsion de tension réelle en ignorant les phénomènes indésirables ou non pertinents tels que les dépassements (voir Figure 1).

3.1.13
durée de l'impulsion
t_d
intervalle de temps pendant lequel la valeur instantanée de l'impulsion dépasse 50 % de l'amplitude de l'impulsion

$$L_p = \frac{U_m}{\Delta i_m / t_d}$$

où

L_p est l'inductance de l'impulsion

Δi_m est la variation totale de i_m pendant l'impulsion

VOIR: Figure F.1.

Note 1 à l'article: Pour les impulsions unidirectionnelles $\Delta i_m = \hat{\imath}_m$.

3.1.14
facteur d'inductance de l'impulsion
A_{LP}
inductance de l'impulsion divisée par le carré du nombre de tours de la bobine d'essai

$$A_{LP} = \frac{L_p}{N^2}$$

3.1.15
limite du produit tension-temps
$(U \cdot t)_{\mathrm{lim}}$
limite spécifiée du produit de l'amplitude d'une impulsion de tension et du temps écoulé depuis le début de l'impulsion

Note 1 à l'article: Dans cette limite, il convient que la non-linéarité du courant magnétisant à travers la bobine de mesure placée sur le noyau ne dépasse pas une valeur spécifiée.

3.1.16
non-linéarité (dans le temps)
rapport de la valeur instantanée réelle d'une caractéristique à un instant t à la valeur atteinte par la portion linéaire extrapolée de ce graphique en fonction du temps, au même instant

VOIR: Figure F.3.

3.1.17
taux de répétition des impulsions
fréquence de récurrence des impulsions dans une séquence périodique d'impulsions

3.2 Symboles

Toutes les formules du présent document utilisent des unités SI de base. Lorsque des multiples ou des sous-multiples sont utilisés, la puissance de 10 appropriée doit être introduite.

A_{e} section effective du noyau
$\hat{B}_{\mathrm{e}}$ valeur de crête de l'induction magnétique effective dans le noyau
f fréquence
$\hat{H}_{\mathrm{e}}$ valeur de crête du champ magnétique effectif dans le noyau
l_{e} longueur du chemin magnétique effectif du noyau
L inductance
i valeur instantanée du courant
I courant
N nombre de tours de l'enroulement de la bobine de mesure
P perte de puissance dans le noyau
Q facteur de qualité du noyau pour une fréquence donnée
R résistance
t temps
T température
u valeur instantanée de la tension
U tension
V_{e} volume effectif du noyau
δ erreur relative, déviation, etc.
Δ erreur absolue, déviation, etc.
μ_{ea} perméabilité d'amplitude effective
μ_0 perméabilité du vide: environ $4\pi \times 10^{-7}$ H/m
φ déphasage
ω pulsation = $2\pi f$

NOTE 1 Les indices, les exposants, etc. supplémentaires donnent une signification plus spécifique au symbole donné.

NOTE 2 Les symboles utilisés de manière exceptionnelle sont définis à l'emplacement où ils apparaissent dans le texte.

NOTE 3 Les paramètres effectifs tels que la longueur du chemin magnétique effectif, l_e, la section effective, A_e, et le volume effectif du noyau, V_e, sont calculés conformément à l'IEC 60205.

NOTE 4 Dans le texte du présent document, le terme induction est utilisé comme abréviation d'induction magnétique.

4 Exigences générales pour les mesures à niveau élevé d'excitation

4.1 Indications générales

4.1.1 Relation avec la pratique

Les conditions, les méthodes et les procédures de mesure doivent être choisies de manière que les résultats mesurés soient adaptés à la prédiction des performances du noyau dans des circonstances pratiques. Cela n'implique pas que toutes ces stipulations, en particulier celles liées aux formes d'onde d'excitation, doivent correspondre aux termes rencontrés en pratique.

4.1.2 Paramètres effectifs de noyau et propriétés des matériaux

La section du noyau n'étant généralement pas uniforme et celui-ci n'ayant en général pas d'enroulements uniformément répartis le long du chemin de noyau, la mesure ne donne ni la perméabilité d'amplitude ni la perte de puissance du matériau, mais des valeurs effectives de ces paramètres qui sont appropriées à l'induction magnétique effective $\hat{B}_e$ et au champ magnétique effectif $\hat{H}_e$ dans le noyau.

Pour la mesure de la perméabilité d'amplitude et de la perte de puissance du matériau, le noyau doit avoir une forme d'anneau ou une forme toroïdale dans laquelle il convient que le rapport du diamètre extérieur sur le diamètre intérieur ne soit pas supérieur à 1,4 avec des enroulements répartis uniformément près du noyau qui ont un coefficient de couplage inductif pratiquement égal à un.

4.1.3 Reproductibilité de l'état magnétique

Pour éviter différents effets de rémanence et de temps dans le matériau du noyau, le mesurage doit être effectué avec un état magnétique reproductible et bien défini.

Sauf indication contraire, tout mesurage avec une excitation spécifiée doit être effectué au moment $t_m = t_c + \Delta t$ après le début du conditionnement magnétique; t_c est le temps nécessaire pour que le conditionnement magnétique soit terminé et sert de base pour le réglage de l'excitation spécifiée; Δt est la durée pendant laquelle le noyau est maintenu stable au niveau d'excitation réglé.

4.2 Bobine de mesure

4.2.1 Généralités

Une bobine de mesure est normalement utilisée, mais en principe, toute ligne coaxiale, cavité ou tout autre dispositif approprié qui assure l'interaction nécessaire entre le matériau magnétique et le signal électromagnétique peut également être utilisé.

Pour le mesurage sur tore avec des bobines, les spires de la bobine de mesure doivent être réparties de manière à maintenir à la fois la capacité parasite et le champ parasite à une valeur aussi faible que nécessaire pour obtenir une mesure suffisamment exacte.

Pour les mesurages réalisés sur noyaux assemblés autour d'une bobine, la forme de la bobine de mesure doit correspondre à celle des bobines utilisées pour l'application normale du noyau et son influence sur la variation de l'inductance à mesurer doit être négligeable.

Sauf spécification contraire, la bobine d'essai complète avec support de bobine ou encapsulation, ou les deux, doit être positionnée de façon coaxiale par rapport à la branche qu'elle entoure, et le côté de la bobine où se trouve le début de l'enroulement doit être légèrement pressé contre le noyau à une extrémité de cette branche, comme suit:

- dans le cas d'un noyau symétrique, la bobine doit être en contact avec le noyau à l'une ou l'autre des extrémités;
- dans le cas d'un noyau avec un entrefer qui est asymétrique, ce dernier ayant été réalisé par rodage du matériau sur le côté d'une moitié du noyau et non sur l'autre, la bobine doit présenter le contact d'extrémité sur la moitié du noyau qui n'a pas été rodée pour créer l'entrefer.

L'une des faces de la bobine doit être marquée pour définir son orientation. La bobine doit être maintenue dans la position définie pendant toute la durée du mesurage afin d'obtenir une reproductibilité maximale de la mesure.

4.2.2 Nombre de tours

Le nombre de tours doit être spécifié pour chaque enroulement en relation avec les conditions de mesure, l'équipement utilisé et l'exactitude à obtenir. Les enroulements doivent être réalisés aussi près que possible du noyau, pour rendre les coefficients de couplage (lien de flux magnétique) entre les enroulements de la bobine de mesure et le noyau et entre les enroulements de la bobine de mesure aussi proches que possible de 100 %.

Il convient que la résistance, la capacité répartie et la capacité inter-enroulements des enroulements soient aussi faibles que possible pour rendre les erreurs liées négligeables.

Dans le cas de noyaux en anneau ou toroïdaux, les spires doivent être réparties de manière régulière sur la circonférence du noyau.

Il convient que les connecteurs, essentiellement ceux de l'enroulement d'excitation, soient constitués d'éléments isolés, si cela est nécessaire pour les mesures à hautes fréquences.

Lors du bobinage d'un noyau à arêtes vives, il convient que l'isolation du fil ne se rompe pas et, dans le cas d'un fil multibrin, il convient que les éléments ne se cassent pas.

4.2.3 Enroulement unique et enroulement double

L'utilisation d'un enroulement unique à la fois pour l'excitation et la détection de tension est recommandée si

– le couplage entre l'enroulement d'excitation et l'enroulement de détection de tension est réduit d'une manière telle qu'il provoque une erreur non négligeable dans la détermination de l'induction magnétique de mesure B dans le noyau;
– la capacité inter-enroulements est trop élevée;
– il n'existe pas de contre-indication de circuits de mesure relative à la connexion directe de l'enroulement d'excitation à l'entrée ou aux entrées des instruments de mesure.

Lorsqu'un enroulement unique est utilisé, il est recommandé de rendre sa résistance aussi faible que possible pour rendre la perte de puissance ohmique de l'enroulement négligeable par rapport à la perte de puissance dans le noyau.

L'utilisation d'enroulements d'excitation et de détection de tension séparés (enroulement double) est recommandée si, pour une raison quelconque, l'enroulement d'excitation est séparé galvaniquement des instruments de mesure de la tension et du courant, par exemple pour éviter une connexion flottante ou en courant continu vers leurs entrées.

Lorsque les enroulements d'excitation et de détection de tension sont utilisés, leur coefficient de couplage magnétique doit être aussi proche que possible de 100 %.

La tension nécessaire pour le calcul de l'induction magnétique dans le noyau est habituellement mesurée à travers un enroulement de détection de tension séparé de l'enroulement de courant admissible (d'excitation). Lors du mesurage des pertes du noyau, les pertes ohmiques dans l'enroulement de détection de tension n'ont pas d'influence sur le calcul, mais les pertes ohmiques dans l'enroulement de courant admissible (d'excitation) doivent être exclues du calcul des pertes du noyau.

L'utilisation de deux enroulements est recommandée pour des fréquences supérieures à 200 kHz.

4.3 Montage des noyaux constitués de plus d'une partie

Un noyau ferrite constitué de plus d'une partie et qui doit être assemblé autour de la bobine de mesure doit être fixé avec une colle, une bande adhésive ou un dispositif de fixation pendant toute la durée du mesurage.

Quelle que soit la méthode utilisée pour assembler les parties du noyau, elle doit avoir les caractéristiques suivantes:

- répartition de la force d'application de manière uniforme sur les surfaces d'accouplement, sans introduire de contraintes de déformation dans le noyau;
- maintien de toutes les parties du noyau de manière rigide et sans changer la position des unes par rapport aux autres;
- lorsqu'une méthode d'assemblage spécifiée est utilisée, une surforce initiale d'environ 10 % doit être appliquée lorsque le noyau est fermé, pour casser les petites irrégularités entre les surfaces d'accouplement nettoyées. La force d'assemblage spécifiée de ±5 % doit ensuite être appliquée;
- maintien à un niveau constant de la force d'assemblage à ±1 % pendant toutes les opérations de mesure dans toutes les conditions de mesure, y compris la plage complète de températures spécifiées.

Le montage de tels noyaux doit être effectué conformément aux instructions suivantes.

La surface d'accouplement doit être examinée pour constater les dommages et la propreté. Des noyaux endommagés ne doivent pas être utilisés. La surface d'accouplement doit être nettoyée avec des procédés non abrasifs, par exemple en frottant doucement sur un cuir de lavage sec. Ensuite, les surfaces d'accouplement doivent être dégraissées si elles doivent être collées. Les particules de poussières doivent être éliminées avec de l'air comprimé sec et propre. Les surfaces d'accouplement ne doivent jamais être touchées à mains nues. Les parties du noyau doivent ensuite être assemblées autour de la bobine de mesure, celle-ci étant verrouillée en position par rapport au noyau par des moyens adaptés, par exemple une rondelle en mousse. Les parties du noyau sont centrées et collées ou placées dans un dispositif de fixation. La colle, si elle est utilisée, doit être étendue de manière uniforme sur la surface d'accouplement pour former un film aussi fin que possible et être ensuite correctement durcie.

Dans le cas où le dispositif de fixation est utilisé, la force de fixation stipulée dans la spécification associée doit être appliquée. Les noyaux collés, bandés ou fixés doivent être laissés au repos dans les conditions spécifiées (voir l'IEC 62044-1:2002, Article 3) pendant une durée suffisante pour permettre à toute variation des effets de contrainte due à l'assemblage, au collage ou au bandage de devenir négligeable.

4.4 Équipement de mesure

4.4.1 Tout équipement de mesure adapté peut être utilisé. Des exemples de circuits appropriés sont donnés de l'Annexe A à l'Annexe E.

En plus de toute exigence spécifiée pour la méthode particulière ou le circuit de mesure utilisé, ou les deux, les exigences générales suivantes doivent être respectées.

4.4.2 Pour assurer le mode d'excitation par induction magnétique (par champ magnétique), l'impédance de sortie de la source d'excitation doit être faible (élevée) par rapport à l'impédance de série de l'enroulement d'excitation de la bobine de mesure assemblée avec le noyau à l'essai et la résistance de détection de courant.

4.4.3 Lorsque la forme sinusoïdale d'excitation est spécifiée, le contenu harmonique total de la source d'excitation doit être inférieur à 1 %. Lorsque des impulsions carrées sont spécifiées, les exigences applicables de l'Annexe F doivent être respectées.

4.4.4 Pendant le mesurage, les variations d'amplitude d'excitation ne doivent pas dépasser ±0,05 % et la stabilité de fréquence doit être adaptée à la méthode de mesure et à l'équipement utilisé.

4.4.5 La plage de fréquences des voltmètres et des autres instruments de détection de tension doit inclure tous les harmoniques de la tension mesurée qui ont des amplitudes de 1 % ou plus de leurs valeurs fondamentales. La plage de fréquences doit être stipulée dans la spécification d'instrument applicable.

4.4.6 Les voltmètres et les autres instruments de détection de tension utilisés doivent être des instruments à impédance élevée dont la connexion n'a qu'un effet négligeable sur le circuit de mesure, en particulier à haute fréquence. Les sondes de résistance d'entrée élevée et de faible capacité d'entrée peuvent réduire les effets de charge.

4.4.7 L'exactitude des voltmètres ou des instruments de détection de la tension déterminée pour le calibrage des formes d'onde sinusoïdales doit se situer dans une tolérance relative de ±0,5 % pour les valeurs efficaces et moyennes et ±1 % pour les valeurs de crête, dans la mesure où le facteur de crête des formes d'onde à mesurer se situe dans les limites imposées par l'instrument.

Si les inexactitudes dépassent les limites indiquées ci-dessus, il est recommandé d'utiliser uniquement une excitation sinusoïdale d'un contenu harmonique inférieur à 1 %, et

- pour déterminer les valeurs efficace, moyenne et de crête des formes sinusoïdales, il est recommandé d'utiliser un voltmètre de détection de valeur efficace vraie d'une exactitude de ±1 %. Les valeurs moyenne et de crête sont obtenues en multipliant les valeurs efficaces indiquées par les facteurs suivants: valeur moyenne = 0,900 × valeur efficace, valeur de crête = 1,414 × valeur efficace;
- pour déterminer les valeurs efficace, moyenne et de crête des formes non sinusoïdales, un oscilloscope à mémoire et traitement numériques ou des instruments d'acquisition et de traitement appropriés doivent être utilisés. Ces appareils doivent être en mesure de capter et de traiter des formes d'onde avec un taux d'échantillonnage d'au moins 150 échantillons par période de forme d'onde et avec une résolution d'au moins 8 bits.

NOTE Le facteur de crête est le rapport de la valeur de crête sur la valeur efficace de la forme d'onde mesurée.

4.4.8 La valeur de la résistance de la résistance de détection de courant en série doit être connue avec une inexactitude qui ne dépasse pas ±1 chiffre au troisième rang significatif, y compris avec des variations thermiques possibles de la résistance. Une résistance à dissipation de chaleur ou à base refroidie peut modérer les variations thermiques indiquées ci-dessus.

L'inductance L_R de la résistance R dans la plage de fréquences spécifiée en 4.4.5 ne doit pas dépasser une valeur de:

$$L_R \leq \frac{R}{\omega_m}\sqrt{2\delta\hat{U}_R}$$

où

R	est la valeur de la résistance;
$\omega_m = 2\pi f_m$	f_m étant la fréquence la plus élevée dans la plage de fréquences spécifiée en 4.4.5;
$\delta\hat{U}_R$	est l'augmentation relative admise pour la chute de tension $\hat{U}_R$ à travers la résistance R, due à l'inductance L, à la fréquence f_m.

Par exemple, pour $\delta\hat{U}_R = 0{,}1\ \%$, R = 1 Ω et la fréquence la plus élevée f_m = 500 kHz, l'inductance L doit être inférieure à $(2\pi \times 500 \times 10^3)^{-1} \times 1 \times (2 \times 0{,}001)^{0{,}5}$ = 14,2 nH.

La résistance de détection de courant peut être remplacée par une sonde de courant adaptée de manière appropriée dans la mesure où cela ne réduit pas l'exactitude d'amplitude et de phase sur la plage de fréquences, comme cela est exigé en 4.4.5. Par ailleurs, la sonde de courant doit être un dispositif linéaire, c'est-à-dire ne pas générer d'harmoniques.

NOTE Pour la mesure de la perméabilité d'amplitude, l'exactitude d'amplitude de la sonde de courant est essentiellement concernée.

4.4.9 Toutes les connexions entre les composants du circuit doivent être aussi courtes que possible. Par ailleurs, les connexions, si elles sont multiples, donnant un déphasage non égal complémentaire, doivent être de longueur égale et du même type. Tout déphasage $\Delta\varphi$ (radian) entre les voies conçues comme équiphase pour conduire les signaux qui correspondent à l'induction magnétique et au champ magnétique sur la plage de fréquences définie en 4.4.5 ne doit pas dépasser une valeur de:

$$\Delta\varphi = \pm\frac{\delta P(\Delta\varphi)}{Q}$$

où

$\delta P(\Delta\varphi)$	est la part d'inexactitude totale de la mesure de perte de puissance qui est liée au déphasage $\Delta\varphi$;
$Q = \dfrac{\omega\hat{B}_e\hat{H}_e}{2P_v}$	est le facteur de qualité du noyau à l'essai;
$\omega = 2\pi f$	est la pulsation;
$\hat{B}_e$ et $\hat{H}_e$	sont les valeurs de crête de l'induction magnétique effective et du champ magnétique effectif dans le noyau, respectivement;
$P_v = P/V_e$	est la densité de perte de puissance; V_e est le volume effectif du noyau.

Si une excitation non sinusoïdale est appliquée, les déphasages des harmoniques impliqués doivent être déterminés. En correspondance avec chaque fréquence d'harmonique, les valeurs des paramètres indiqués plus haut doivent être utilisées dans le calcul de chaque fréquence harmonique.

Par exemple, $\delta P(\Delta\varphi)$ doit être à ±1 % et Q = 5 pour un noyau et des conditions de mesure donnés. Par conséquent, $\Delta\varphi$ doit être à ±0,01/5 = ±0,002 radian.

4.4.10 Tout contact de connecteurs, de jonctions, d'interrupteurs, de multiplexeurs, etc., intermédiaires qui est associé au circuit de mesure de tension ou de courant doit être en mesure de transmettre les tensions impliquées et les courants de conditionnement et de mesure des valeurs stipulées dans la spécification applicable. La résistance de contact, le déphasage, les couplages inductifs et capacitifs, l'impédance de série et l'admittance parallèle qui résultent de l'insertion du contact ne doivent avoir qu'un effet négligeable sur les résultats mesurés dans toutes les conditions de mesure concernées, y compris la plage de fréquences, comme cela est spécifié en 4.4.5.

4.4.11 Il convient de procéder à des mesurages ou à un étalonnage, ou aux deux, pour s'assurer que l'inexactitude de mesure qui en résulte pour la perméabilité d'amplitude et la perte de puissance sur toutes les conditions de mesure ne dépasse pas l'inexactitude spécifiée pour la méthode de mesure donnée et le circuit spécifié.

4.4.12 Un environnement à température contrôlée doit être prévu, en mesure de maintenir l'équilibre thermique entre le noyau et cet environnement dans des limites de température spécifiées pendant le conditionnement, le réglage, le mesurage et les opérations de lecture.

5 Éprouvettes

Des noyaux prélevés dans la production normale qui forment des circuits magnétiques fermés doivent être utilisés pour la mesure.

6 Procédures de mesure

6.1 Procédure générale

6.1.1 Le noyau à mesurer est assemblé avec la bobine de mesure conformément au 4.3.

Dans le cas de noyaux en anneau et toroïdaux, appliquer les enroulements conformément au 4.2.1.

6.1.2 Le noyau doit être placé dans un environnement à température contrôlée conformément au 4.4.12. Toutes les opérations de mesure telles que le conditionnement magnétique, les réglages et les mesurages doivent être effectuées après obtention de la température du noyau et maintien de celle-ci dans les limites de tolérance admises.

6.1.3 Les tensions qui correspondent à la valeur de crête d'induction magnétique $\hat{B}_e$ et à la valeur de crête du champ magnétique $\hat{H}_e$ auxquelles le mesurage doit être réalisé sont calculées conformément aux formules suivantes:

– pour une excitation $\hat{B}_e$: $U_{av} = 4 \cdot f \cdot N \cdot A_e \cdot \hat{B}_e$

où N est égal à N_1 lorsqu'un seul enroulement (à la fois pour les fonctions d'excitation et de détection de tension) est utilisé et N est égal à N_2 lorsqu'un enroulement secondaire est utilisé pour la détection de tension;

– pour une excitation $\hat{H}_e$:

$$\hat{U}_R = \frac{R \cdot l_e \cdot \hat{H}_e}{N_1}$$

où

$\hat{U}_R$ la valeur de crête de la tension à travers la résistance série R;

N_1 est le nombre de tours de l'enroulement d'excitation N$_1$.

Les symboles sont définis en 3.2, et N_1 est le nombre de tours de l'enroulement d'excitation.

NOTE 1 Pour les formes d'onde d'induction magnétique sinusoïdales pratiquement pures $\hat{B}_e$, la tension qui correspond à $\hat{B}_e$, peut être mesurée en utilisant aussi les voltmètres ou instruments de lecture des valeurs efficaces et de crête. Les valeurs efficace U_{rms} et de crête $\hat{U}$, respectives de cette tension sont calculées comme suit:

$$U_{rms} = \sqrt{2} \cdot \pi \cdot f \cdot N \cdot A_e \cdot \hat{B}_e$$

$$\hat{U} = 2 \cdot \pi \cdot f \cdot N \cdot A_e \cdot \hat{B}_e$$

NOTE 2 Si la sonde de courant est utilisée à la place de la résistance R, la valeur de crête du courant $\hat{I}$ qui correspond à $\hat{H}_e$ est calculée comme $\hat{I} = \hat{H}_e$.

NOTE 3 Dans le cas où une section autre que A_e est utilisée, par exemple A_{min}, pour le calcul de U_{av}, cela doit être clairement indiqué dans la spécification applicable.

6.1.4 Le noyau est conditionné par la méthode électrique conformément à l'IEC 62044-1:2002, 5.2a), sauf indication contraire.

6.1.5 Au moment spécifié t_c après le début du conditionnement, la source d'excitation est réglée, aussi rapidement que possible, de préférence à t_c = (2 ± 0,5) s pour les paramètres temporels, à la fréquence, la forme d'onde et l'amplitude d'excitation exigées.

Pour conserver une forme d'onde d'excitation correcte dans toutes les conditions de mesure, il convient de la contrôler. Dans le cas du mode d'excitation par induction magnétique, il convient que l'entrée du dispositif de contrôle soit de préférence connectée à un enroulement de détection de tension séparé.

6.1.6 Au temps t_m, les lectures de mesure doivent être effectuées et l'excitation doit être rapidement coupée. La durée pendant laquelle le noyau est soumis à une excitation spécifiée doit être aussi brève que possible, mais inférieure ou égale à 10 s, pour empêcher le noyau de subir un autoéchauffement excessif.

6.1.7 Lorsqu'un noyau est excité dans des conditions d'impulsions avec ou sans composante de polarisation, les spécifications complémentaires respectives de l'Annexe F doivent être prises en compte.

6.2 Méthode de mesure pour la perméabilité d'amplitude effective

6.2.1 Objet

Fournir une méthode de mesure de la perméabilité d'amplitude effective à des niveaux d'excitation élevés et pour des formes d'onde périodiques symétriques de noyaux magnétiques qui forment des circuits magnétiques fermés.

NOTE En variante, la valeur de crête de l'induction magnétique obtenue à une valeur de crête spécifiée du champ magnétique ou, à défaut, la valeur de crête du champ magnétique à une valeur de crête spécifiée de l'induction magnétique peut être déterminée.

6.2.2 Principe de mesure

L'induction magnétique et le champ magnétique dans un noyau sont déterminés par la mesure de la valeur moyenne de tension par demi-période à travers l'enroulement de détection de tension de la bobine de mesure enroulée sur le noyau et la valeur de crête de la tension à travers la résistance en série avec l'enroulement d'excitation de cette bobine. Les mesurages sont effectués à des valeurs de crête spécifiées d'induction magnétique ou de champ magnétique, de fréquence et de température.

6.2.3 Circuit et équipement

Tout équipement adapté peut être utilisé s'il est capable de remplir la fonction des circuits représentés à l'Annexe A.

Les exigences du 4.4 doivent être respectées. Dans la mesure où les formes d'onde d'induction magnétique et de champ magnétique ne sont pas déterminantes dans le cas de la mesure de la perméabilité d'amplitude, il n'est pas nécessaire de satisfaire rigoureusement aux exigences du 4.4.2 et du 4.4.3.

Si la perméabilité d'amplitude doit être déterminée pour les valeurs de crête des composantes fondamentales des formes d'onde de l'induction magnétique et du champ magnétique, il convient de mesurer ces valeurs de crête avec des instruments à choix de fréquence qui respectent les exigences du 4.4.

6.2.4 Procédure de mesure

La procédure générale du 6.1 doit être appliquée.

Pour la valeur moyenne spécifiée U_{av} de la tension à travers l'enroulement de détection de tension, la valeur de crête $\hat{U}_R$ de la tension à travers la résistance R ou la valeur de crête $\hat{I}$ du courant à travers l'enroulement d'excitation est lue.

Pour l'excitation du champ magnétique, la valeur de U_{av} est lue à une valeur spécifiée de $\hat{U}_R$ ou $\hat{I}$.

NOTE Lorsque la spécification exige de mesurer l'induction magnétique avec un champ magnétique spécifié ou, inversement, le champ magnétique avec l'induction magnétique spécifiée, la valeur de crête spécifiée de l'excitation est réglée, et soit la valeur $\hat{B}_e$ résultante soit la valeur $\hat{H}_e$ résultante est déterminée, respectivement.

6.2.5 Calcul

La perméabilité d'amplitude effective est déduite de

$$\mu_{ea} = \frac{\hat{B}_e}{\mu_0 \cdot} = \frac{l_e R}{4 \cdot \mu_0 \cdot f \cdot N_1 \cdot N_2 \cdot A_e} \cdot \frac{U_{av}}{\hat{U}_R}$$

ou si la sonde de courant est utilisée à la place de la résistance R:

$$\mu_{ea} = \frac{l_e}{4 \cdot \mu_0 \cdot f \cdot N_1 \cdot N_2 \cdot A_e} \cdot \frac{U_{av}}{\hat{I}}$$ où

U_{av} est la valeur moyenne de la tension à travers l'enroulement de détection de tension N_2;

$\hat{U}_R$ est la valeur de crête de la tension à travers la résistance série R;

$\hat{I}$ est la valeur de crête du courant qui traverse l'enroulement d'excitation N_1;

N_1 est le nombre de tours de l'enroulement d'excitation N_1;