

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Magnetic materials –

Part 18: Permanent magnet (magnetically hard) materials – Methods of measurement of the magnetic properties in an open magnetic circuit using a superconducting magnet

Matériaux magnétiques –

Partie 18: Matériaux (magnétiques durs) pour aimants permanents – Méthodes de mesure des propriétés magnétiques en circuit magnétique ouvert à l'aide d'un aimant supraconducteur



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

MAGNETIC MATERIALS –

**Part 18: Permanent magnet (magnetically hard) materials –
Methods of measurement of the magnetic properties in
an open magnetic circuit using a superconducting magnet**

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Draft	Report on voting
68/768/CDV	68/775/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.

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INTRODUCTION

High-performance permanent magnet materials with high coercivity, for example Nd-Fe-B magnets, have been used in the electric and automobile industry and their usage increases rapidly to meet the need to improve energy saving and to increase efficiency of electromagnetic applications, for example traction motors for electric vehicles (EV) and hybrid electric vehicles (HEV), which are urgently demanded to contribute to the problem of global warming.

However, there has been no standard method which can determine all the magnetic properties of the high-performance permanent magnet materials with coercivity H_{cJ} higher than 2 MA/m to meet the need of the industry. The method specified in IEC 60404-5, which is a method of measurement in a closed magnetic circuit, can lead to significant measurement errors for measurement of $H_{cJ} \geq 1,6$ MA/m due to magnetic saturation in parts of the pole faces of the yoke (see IEC 60404-5).

In order to solve the problem, several methods of measurement in an open magnetic circuit without a yoke have been developed. The methods using a superconducting magnet (SCM) are thought to solve this problem and enable accurate measurements of the high-performance permanent magnet materials (see IEC TR 63304 [1]¹).

Since the measurement in an open magnetic circuit is strongly affected by the self-demagnetizing field in the test specimen, a correction of the influence of self-demagnetizing field (demagnetizing field correction) on the demagnetization curve obtained in an open magnetic circuit is indispensable.

¹ Numbers in square brackets refer to the Bibliography.

MAGNETIC MATERIALS –

Part 18: Permanent magnet (magnetically hard) materials – Methods of measurement of the magnetic properties in an open magnetic circuit using a superconducting magnet

1 Scope

The purpose of this part of IEC 60404 is to define the general principle and technical details of the methods of measurement of the DC magnetic properties of permanent magnet materials in an open magnetic circuit using a superconducting magnet (SCM).

This method is applicable to permanent magnet materials, such as those specified in IEC 60404-8-1, the properties of which are presumed homogeneous throughout their volume.

There are two methods:

- the SCM-vibrating sample magnetometer (VSM) method;
- the SCM-extraction method.

This document also specifies methods to correct the influence of the self-demagnetizing field in the test specimen on the demagnetization curve obtained in an open magnetic circuit. The magnetic properties are determined from the corrected demagnetization curve.

NOTE 1 These SCM-methods can determine the magnetic properties of high-performance permanent magnet materials with coercivity higher than 2 MA/m. For the magnetic materials with coercivity higher than 1,6 MA/m, the methods of measurement in a closed magnetic circuit in accordance with IEC 60404-5 can lead to significant measurement error due to magnetic saturation in parts of the pole faces of the yoke (see IEC 60404-5).

NOTE 2 There is another method of the measurement in an open magnetic circuit, i.e. the pulsed field magnetometer (PFM), which is described in IEC TR 62331 [3]. The PFM is the method of measurement of the magnetic properties of permanent magnet materials applying the pulsed magnetic field instead of the DC magnetic field and is different from the methods described in this document. The PFM measures a steep AC magnetic response of a test specimen in a pulsed magnetic field. Consequently, additional correction is indispensable to remove the influence of eddy currents in the test specimen and the magnetic viscosity of the magnetic materials in order to obtain properties equivalent to the DC magnetic properties.

2 Normative references

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

IEC 60050-121:1998, *International Electrotechnical Vocabulary (IEV) – Part 121: Electromagnetism*

IEC 60050-151, *International Electrotechnical Vocabulary (IEV) – Part 151: Electrical and magnetic devices*

IEC 60050-221:1990, *International Electrotechnical Vocabulary (IEV) – Part 221: Magnetic materials and components*

IEC 60404-5, *Magnetic materials – Part 5: Permanent magnet (magnetically hard) materials – Methods of measurement of magnetic properties*

IEC 60404-8-1, *Magnetic materials – Part 8-1: Specifications for individual materials – Permanent magnet (magnetically hard) materials*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-121, IEC 60050-151, IEC 60050-221 and the following apply.

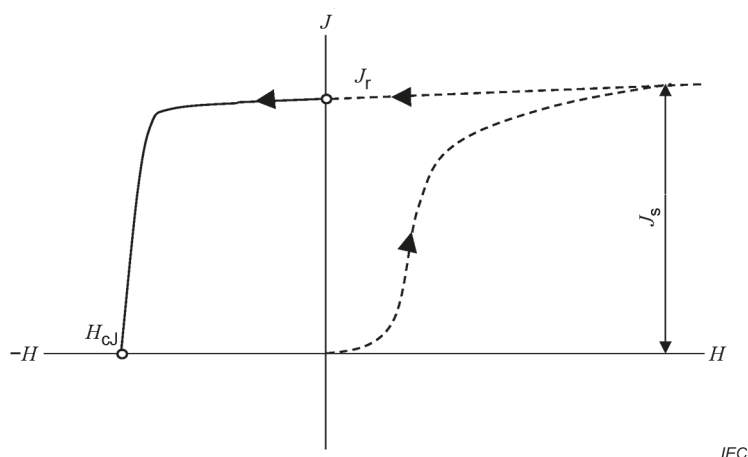
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3.1.1

demagnetization curve

part of a hysteresis loop in which the magnetic polarization goes from the remanent magnetic polarization to zero when the applied magnetic field strength varies monotonically, as illustrated in Figure 1



Key

- J_s saturation magnetic polarization, in T
- J_r remanent magnetic polarization, in T
- H_{cJ} coercivity relating to the magnetic polarization, in A/m

Figure 1 – Demagnetization curve $J(H)$

Note 1 to entry: A demagnetization curve can be drawn from near magnetic saturation.

[SOURCE: IEC 60050-121:1998, 121-12-72, modified – "magnetic flux density" is replaced by "magnetic polarization" and Note 1 to entry and Figure 1 have been added.]

3.1.2

magnetic dipole moment

m

vector quantity given by the volume integral of the magnetic polarization

[SOURCE: IEC 60050-221:1990, 221-01-07, modified – the symbol j is changed to m which is used industrially and the note has been removed.]

3.1.3

***M* coil**

detection coil for magnetic dipole moment

3.2 Abbreviated terms

ADC	analogue-to-digital converter
EV	electric vehicle
FEM	finite element method
HEV	hybrid electric vehicle
NMR	nuclear magnetic resonance
PC	personal computer
PFM	pulsed field magnetometer
SCM	superconducting magnet
SQUID	superconducting quantum interference device
VSM	vibrating sample magnetometer

4 General principle

4.1 Principle of the method

Figure 2 illustrates schematic diagrams of the test apparatus corresponding to a) the SCM-VSM method and b) the SCM-extraction method. The test apparatus consists of a superconducting magnet (SCM), a moving device, a specimen rod, a magnetic field sensor (hereafter *H* sensor), a magnetic dipole moment detection coil (hereafter *M* coil), measuring devices and a data processing device (PC).

The axis of the DC magnetic field generated by the SCM shall be vertical and coaxial with the *M* coil and the specimen rod so that the direction of magnetization is parallel to the axis of the specimen rod. The moving range of the test specimen shall be in a zone where the magnetic field strength is uniform with a tolerance of ± 1 % at the centre of the SCM. The *H* sensor shall be placed in a position where the influence of the magnetic dipole moment of the test specimen can be ignored.

The test specimen shall be firmly attached at the bottom end of the specimen rod to avoid unexpected movement of the test specimen in the magnetic field and placed in the centre of the SCM as shown in Figure 2.

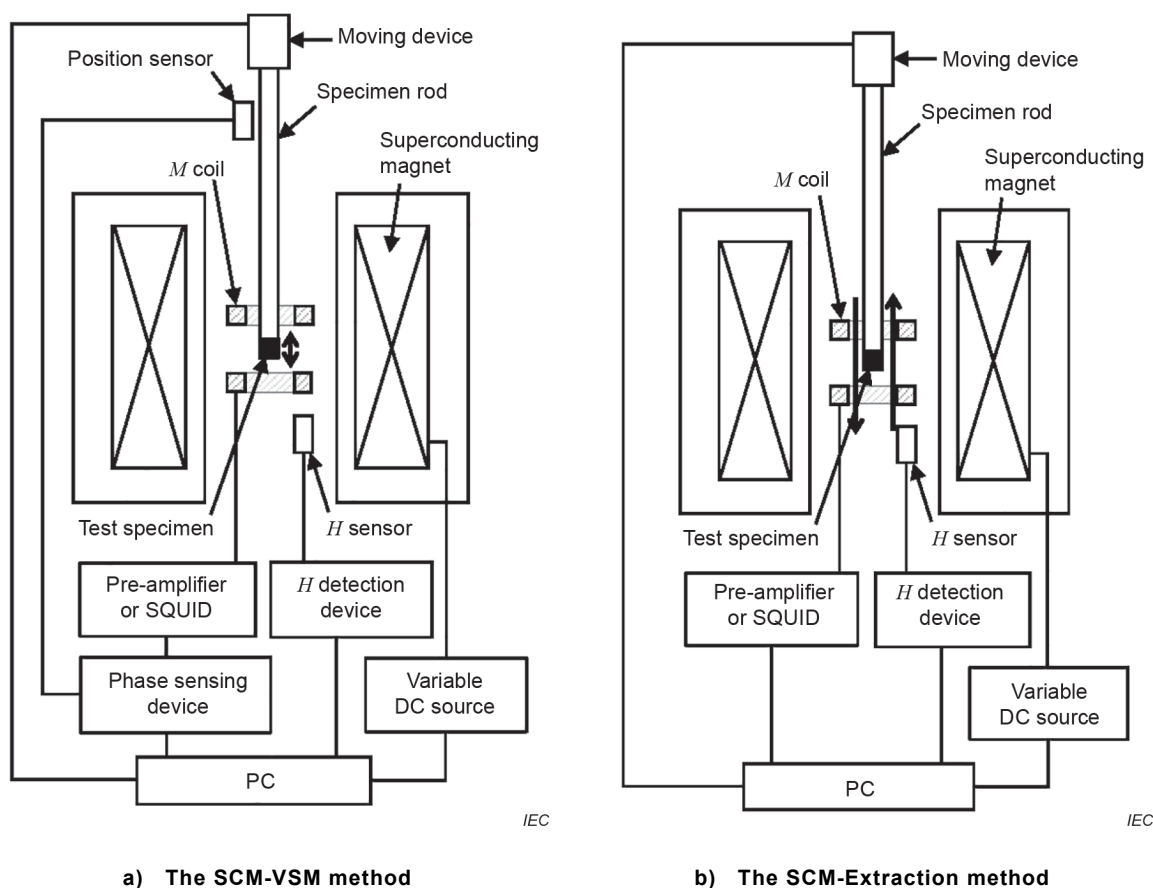


Figure 2 – Schematic diagrams of the test apparatus

The test specimen shall be initially magnetized to saturation (see 6.2) and be kept in the remanent state. A DC magnetic field shall be applied to the test specimen in the direction opposite to that used for the initial magnetization. The magnetic field strength is measured by the H sensor (see 4.3).

The magnetic dipole moment of the test specimen is detected by the voltage induced in the M coil due to the movement of the test specimen (see 4.4). The magnetic polarization of the test specimen is calculated from the magnetic dipole moment and the volume of the test specimen (see 7.2). For calibration aspects, see Clause 9.

There are two methods different in modes of the movement of the test specimen:

- a) the SCM-VSM method: the test specimen is vibrated with a small amplitude in the M coil;
- b) the SCM-extraction method: the test specimen is extracted through the M coil.

The measurements shall be carried out at an ambient temperature of $(23 \pm 5) ^\circ\text{C}$ unless otherwise indicated.

NOTE The measurement at temperatures higher than the room temperature can be carried out using a heating unit (see Annex C).

For permanent magnet materials which are known to have significant temperature coefficients $\alpha(J_r)$ and $\alpha(H_{cJ})$, the temperature of the test specimen shall be controlled within $\pm 1 ^\circ\text{C}$ in the range between $19 ^\circ\text{C}$ and $27 ^\circ\text{C}$ during the measurements (see IEC 60404-5). The temperature of the test specimen shall be measured by a non-magnetic temperature sensor attached directly to the test specimen.

The demagnetization curve obtained in an open magnetic circuit is influenced strongly by the self-demagnetizing field in the test specimen which opposes magnetization.

In order to determine the intrinsic demagnetization curve of the permanent magnet material, a correction of the influence of the self-demagnetizing field (hereafter demagnetizing field correction) shall be applied to the obtained demagnetization curve (see Clause 11). Magnetic properties of the permanent magnet material shall be determined from the corrected demagnetization curve.

4.2 Superconducting magnet (SCM)

A variable DC source supplies a DC current to the superconducting coil, with sufficiently low voltage noise (see Figure 2). The current source shall be a bipolar type which can switch positive-negative polarity continuously.

The SCM shall have enough capacity to generate a magnetic field strength to measure the magnetic properties of high-performance permanent magnet materials with coercivity higher than 2 MA/m, for example Nd-Fe-B sintered magnets. The capacity should be higher than 4,8 MA/m (6 T in magnetic flux density).

There are two types of SCM: the conventional metallic SCM made of metallic superconducting coil and the ceramic SCM made of ceramic high temperature superconducting coil [1].

The ceramic SCM is recommended rather than the conventional metallic SCM, in order to reduce the time required to obtain a demagnetization curve within several minutes and to eliminate the use of expensive liquid helium and its incidental facilities, and this is particularly convenient for industrial use [1].

NOTE The test apparatus using the ceramic SCM which can deal test specimens of industrial size is available worldwide.

The zone of uniform magnetic field strength generated at the centre of the SCM shall be sufficiently large to include the space of the moving test specimen.

4.3 Magnetic field strength sensor (H sensor)

An H sensor, for example a Hall probe, measures the magnetic field strength together with a suitable H detection device (see Figure 2). The H sensor shall be calibrated by an appropriate method such as nuclear magnetic resonance (NMR).

In the case of an SCM whose magnetic field strength is calibrated for the magnetizing current, the magnetic field strength may be determined from the magnetizing current supplied to the SCM. However, A small hysteresis shall be avoided between the magnetizing current and the magnetic field strength of the SCM. In the case that it is not possible to avoid the small hysteresis, the relationship between magnetizing current and magnetic field strength should be precisely evaluated for increase and decrease of the magnetizing current.

The total measuring error of the magnetic field strength shall be smaller than ± 1 %.

4.4 Magnetic dipole moment detection coil (M coil)

The M coil measures the magnetic dipole moment of the test specimen by the voltage induced in it (see Figure 2). The M coil shall be wound coaxially with the axis of magnetic field and placed symmetrically with respect to the centre of the magnetic field. Electrical leads of the M coil shall be tightly twisted to avoid errors caused by voltages induced in loops of the leads.

The voltage induced in the M coil shall be calibrated using a standard specimen of nickel sphere and the influence of the shape and dimensions of the test specimen on the voltage shall be verified (see Clause 9).

The total measuring error of the magnetic dipole moment shall be smaller than $\pm 1\%$.

The M coil used in this document is the first order gradiometer coil which shall be composed of an upper coil and a lower coil connected electrically in opposite polarity as shown in Figure 3. The second order gradiometer coil combined with a SQUID (superconducting quantum interference device) circuit may also be used for the M coil [1].

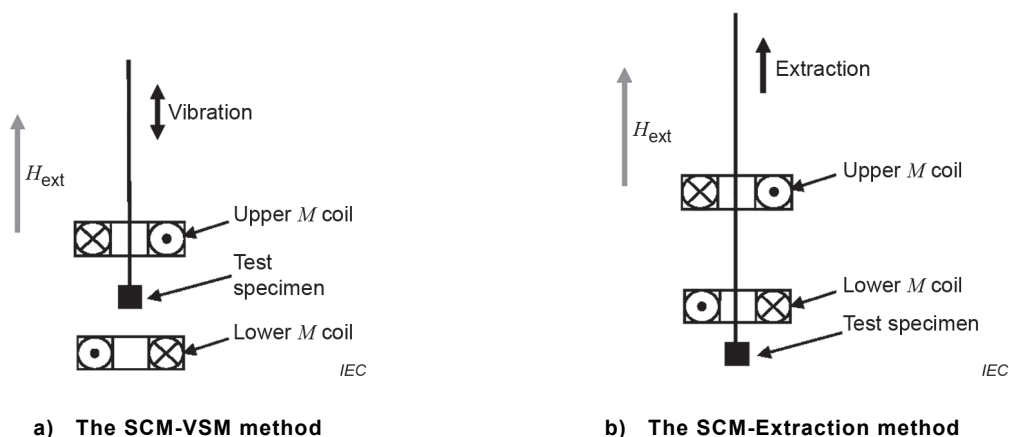


Figure 3 – Schematic diagrams of the first order gradiometer coil

4.5 Specimen rod and moving device

The specimen rod shall be non-magnetic and shall have high rigidity to keep the test specimen on the axis of the magnetic field without trembling.

The specimen rod shall be inserted vertically in the SCM and connected to the moving device at the top end as shown in Figure 2.

The moving device may be a linear motor, a voice coil or other system which can move or vibrate the specimen rod linearly along the axis of the magnetic field.

Moving modes of the test specimen are as follows.

a) The SCM-VSM method

The test specimen is vibrated along the axis of the magnetic field at a fixed frequency and a fixed amplitude sufficiently smaller than the length of the M coil. The frequency is normally 20 Hz to 200 Hz and the amplitude is typically from 0,5 mm to 2 mm (see Figure 3 a)).

b) The SCM-extraction method

The test specimen is extracted through the M coil along the axis of the magnetic field. The start point of the moving specimen is below the lower M coil or above the upper M coil (see Figure 3 b)).

4.6 Measuring devices and data processing device

The voltage induced in the calibrated M coil due to the movement of the test specimen is proportional to the magnetic dipole moment of the test specimen. The signal of the M coil is fed to a preamplifier. In the case of the second order gradiometer coil, a SQUID circuit shall be employed to integrate the signal (see Figure 2).

In the SCM-VSM method, the amplified signal is fed to a phase sensing device such as a lock-in amplifier to output the amplitude of the signal synchronized to the vibration frequency of the test specimen. The output signal is fed to the data processing device.

NOTE In the SCM-VSM method, there is no drift in the signal of the magnetic dipole moment, owing to the use of a phase sensing device (lock-in amplifier) in the SCM-VSM.

In the SCM-extraction method, the amplified signal is directly fed to the data processing device.

The output signal of the H detection device, which is proportional to the magnetic field strength, is fed to the data processing device.

The data processing device is usually composed of a digitizer and a digital signal calculator for the determination of the magnetic properties. The digitizer converts the input signals into digital data simultaneously with analogue-to-digital converters (ADC). The ADC shall have at least a 16-bit resolution.

The digital signal calculator is usually a personal computer (PC) and calculates the magnetic properties from the digitized signals of the magnetic dipole moment and the magnetic field strength.

5 Test specimen

The shape of the test specimen shall be a cylinder or cuboid.

The ratio of the length L to the dimension D , i.e. L/D , shall be 1,00 within $\pm 0,05$, where D is the edge length of the cuboid test specimen or the diameter of the cylinder test specimen. In the case of a cuboid with $L/D = 1,00$, the direction of magnetization shall be marked properly during the test specimen preparation. The direction of magnetization shall be parallel to the length L of the specimen.

NOTE 1 A small difference between L and D of a cuboid test specimen is convenient to easily identify the magnetizing direction of the test specimen.

The dimensions of the test specimen, i.e. L and D , shall be equal to or larger than 3 mm but sufficiently smaller than that of the M coil [1].

The test specimen shall be cut carefully to the predetermined dimension from a large block of the permanent magnet material. Damage on its surface shall be avoided as much as possible, which can deteriorate the magnetic properties.

Test specimens with a dimension less than 3 mm may be used, provided that the damaged surface layer is negligible or a special treatment is applied on the damaged surface layer to recover the intrinsic magnetic properties.

The test specimen should be marked with an arrow to indicate the direction of magnetization in order to make it easy to attach the test specimen to the specimen rod.

NOTE 2 The thickness of permanent magnet materials used in industry has become thinner as their magnetic properties have improved, and permanent magnets thinner than 5 mm have come to be widely used in industry. It is not impossible to measure the magnetic properties of permanent magnet materials with test specimens obtained from these magnets by the conventional test method described in IEC 60404-5 that defines the dimensions of the test specimens to be 5 mm or more. Therefore, a new test method to measure magnetic properties of permanent magnet materials for smaller test specimen has been required by industry. Fundamentally, for test specimens smaller than 5 mm cube, the measurement reproducibility of the conventional closed magnetic circuit measurement becomes worse by influence of the air-gap between the test specimen and the pole pieces. The air-gap caused by poor machining accuracy generates local demagnetizing field in the test specimen and tends to create a risk of cracking. Due to these backgrounds, the open magnetic circuit measurement is required in industry.

6 Preparation of measurement

6.1 Measurement of volume of the test specimen

The volume V of the test specimen shall be calculated from the mass and the density of the test specimen. The mass of the test specimen shall be determined accurately by means of a calibrated electronic balance. The density of the test specimen shall be determined accurately with a large block of the permanent magnet material, for example water displacement measurement based on Archimedean principle.

The volume V can also be calculated from the dimensions of the test specimen measured by means of a calibrated micrometer with four significant figures.

The volume V of the test specimen shall be determined within a tolerance of $\pm 1\%$.

6.2 Initial magnetization of the test specimen to saturation

Before measurement, the test specimen shall be magnetized to saturation in a DC magnetic field strength H_{mag} .

If it is not possible to magnetize the test specimen to saturation in the test apparatus, the test specimen shall be magnetized to saturation outside the test apparatus in a superconducting coil or a pulse magnetizer in accordance with IEC 60404-5.

Recommended values for the DC magnetic field strength H_{mag} for various permanent magnet materials can be found in IEC TR 62517 [4].

7 Determination of magnetic polarization

7.1 Measurement of the magnetic dipole moment

7.1.1 SCM-VSM method

In the SCM-VSM method, the test specimen shall be vibrated at a fixed frequency and a fixed amplitude, and then the output voltage of the phase sensing device shall be measured (see 4.6).

The magnetic dipole moment m shall be calculated from Formula (1):

$$m = \frac{C_V U_V}{a \cdot f} \quad (1)$$

where

m is the magnetic dipole moment, in $\text{Wb} \cdot \text{m}$;

U_V is the output voltage of the phase sensing device, in V;

C_V is a constant, in m^2 ;

a is the amplitude of the vibration, in m;

f is the frequency of the vibration, in Hz.

The constant C_V shall be determined by a calibration of the M coil (see Clause 9).

7.1.2 SCM-extraction method

In the SCM-extraction method, the test specimen shall be extracted through the M coil. The output voltage of the preamplifier or the SQUID circuit shall be measured (see 4.6).

The magnetic dipole moment shall be calculated from Formula (2):

$$m = C_1 \int_{t_1}^{t_2} U(t) dt \quad (2)$$

where

m is the magnetic dipole moment, in $\text{Wb} \cdot \text{m}$;

$U(t)$ is the output voltage of the preamplifier or the SQUID circuit, in V;

t_1 is the time when the test specimen goes through the lower part of the M coil and $U(t_1) = 0$, in s;

t_2 is the time when the test specimen goes through the upper part of the M coil and $U(t_2) = 0$, in s;

C_1 is a constant, in m .

The constant C_1 shall be determined by a calibration of the M coil (see Clause 9).

7.2 Determination of magnetic polarization

The magnetic polarization J shall be calculated from the magnetic dipole moment m and the volume of the test specimen V according to Formula (3).

$$J = \frac{m}{V} \quad (3)$$

where

J is the magnetic polarization, in T;

m is the magnetic dipole moment, in $\text{Wb} \cdot \text{m}$;

V is the volume of the test specimen, in m^3 .

8 Measurement of magnetic field

The magnetic field strength H corresponding to the magnetic polarization shall be measured by the calibrated H sensor, for example a Hall probe, and the H detection device (see Figure 2).

The temperature dependence of the measuring instrument shall be taken into account.

9 Calibration of the magnetic dipole moment detection coil (M coil)

The calibration of the M coil shall be carried out by measuring a standard specimen of nickel sphere for which the magnetic dipole moment m at an ambient temperature of $(23 \pm 5) ^\circ\text{C}$ and an applied magnetic field strength of 398 kA/m (5 kOe) is certified by a national or accredited calibration laboratory with the temperature coefficient [5]. The standard specimen shall be made of 99,9 % or higher purity nickel and stress-relief annealed without oxidation. The space occupied by the standard specimen including its movement during the measurement shall be sufficiently smaller than the uniform field zone of the SCM coil. Then, the magnetic field generated by the standard specimen is a perfect dipole field and identical to the field generated by an ideal dipole in the centre of the spherical standard specimen.

NOTE A saturation magnetic moment of the standard specimen is not suitable for calibration in this document.

The constant C_V of Formula (1) or C_1 of Formula (2) shall be determined so that the measured magnetic dipole moment at magnetic field strength of 398 kA/m (5 kOe) matches with the certified value of magnetic dipole moment of the nickel sphere. The difference between the ambient temperatures at the calibration and that specified in the certification shall be compensated by using the temperature coefficient specified in the certification.

The shape and dimension dependence of the measured magnetic dipole moment of the test specimen shall be verified and compensated. The verification shall be carried out by comparison of measurements using a standard specimen of nickel sphere and a nickel cuboid or cylinder with the same shape and dimensions as the test specimen. The nickel cube or cylinder shall be made of the same material of 99,9 % or higher purity nickel and stress-relief annealed without oxidation.

10 Determination of demagnetization curve

The demagnetization curve is a part of the hysteresis loop $J(H)$ (see Figure 1). The measurement procedure of the demagnetization curve is as follows.

At first, the test specimen shall be placed in the centre of the SCM as shown in Figure 2. The position of the test specimen shall be adjusted vertically and horizontally at the centre of the M coil looking at the M coil signal in the case of outside saturation magnetization.

The test specimen shall be initially magnetized to saturation and be kept in the remanent state. When the initial saturation of the test specimen is performed in the test apparatus, the magnetizing current supplied to the SCM shall be increased to magnetize the test specimen to saturation and then the magnetizing current shall be reduced to zero to reach zero external magnetic field strength.

A DC magnetic field shall be applied to the test specimen in the direction opposite to that used for the initial magnetization and increased until the magnetic field strength has passed the coercivity H_{cJ} .

The speed of variation of the magnetic field strength shall be sufficiently slow in accordance with IEC 60404-5 to avoid significant magnetic viscosity and eddy currents which can affect the measured value.

The magnetic dipole moment of the test specimen shall be measured by vibrating the test specimen in the M coil (SCM-VSM method) or by extracting the test specimen through the M coil (SCM-Extraction method) (see 7.1). The corresponding magnetic field strength shall be measured.

The demagnetization curve is obtained either from a continuous measurement with a change of the magnetic field strength or from point-by-point measurements at discrete magnetic field strength.

The value of magnetic polarization is determined from the measured value of the magnetic dipole moment (see 7.2), and then the demagnetization curve $J(H)$ is drawn relating values of the magnetic polarization to the corresponding values of the magnetic field strength.

The obtained demagnetization curve is influenced strongly by the self-demagnetizing field in the test specimen. Therefore, in order to determine the intrinsic demagnetization curve and the principal magnetic properties, the demagnetizing field correction shall be applied on the obtained demagnetization curve.

11 Demagnetizing field correction

11.1 General

There are three methods of the demagnetizing field correction:

- Method A: the method using a demagnetizing factor determined by the shape of the test specimen only;
- Method B: the method using a demagnetizing factor determined by the shape and the magnetic susceptibility of the test specimen;
- Method C: the method using an inverse analysis considering the spatial distribution of the self-demagnetizing field strength in the test specimen.

NOTE The difference between the features of these three methods are described in Annex A.

11.2 Method A: Method using a demagnetizing factor determined by the shape of the test specimen only

Method A assumes that the self-demagnetizing field strength in the test specimen is uniform and determined by the shape of the test specimen only. The strength of the self-demagnetizing field shall be calculated from Formula (4).

$$H_d = -N \frac{J}{\mu_0} \quad (4)$$

where

H_d is the strength of the self-demagnetizing field, in A/m;

N is the demagnetizing factor;

J is the magnetic polarization, in T;

μ_0 is the magnetic constant, in H/m; $\mu_0 \cong 4 \pi \times 10^{-7}$.

The demagnetizing factor N shall be calculated from the permeance coefficient P_c of the permanent magnet material, which is determined according to the shape of the test specimen [6],[7].

The obtained demagnetization curve $J(H_{\text{ext}})$ shall be converted to the demagnetization curve $J(H_{\text{eff}})$ using Formula (4) and Formula (5).

$$H_{\text{eff}} = H_{\text{ext}} + H_{\text{d}} \quad (5)$$

where

H_{eff} is the effective magnetic field, in A/m;

H_{ext} is the external magnetic field, in A/m;

H_{d} is the demagnetizing magnetic field, in A/m.

NOTE There is a spatial distribution of the self-demagnetizing field strength in actual magnets except for the case that the shape of the test specimen is ellipsoidal. However, Method A assumes the self-demagnetizing field strength in the test specimen is uniform independently of the shape. Hence the accuracy of this method is not high.

11.3 Method B: Method using a demagnetizing factor determined by the shape and the magnetic susceptibility of the test specimen

Method B calculates the demagnetizing factor N of the test specimen using a finite element method (FEM) with respect to the shape and the magnetic susceptibility χ of the test specimen.

The demagnetizing factor N corresponding to the shape and magnetic susceptibility χ of the test specimen can be found in literature (see Table 1 in [8]).

The obtained demagnetization curve $J(H_{\text{ext}})$ shall be converted to the demagnetization curve $J(H_{\text{eff}})$ using the above demagnetizing factor N and Formula (4) and Formula (5).

NOTE Method B assumes the self-demagnetizing field strength in the test specimen is not uniform and is dependent on the shape and the magnetic susceptibility χ . Hence the accuracy is improved, but it will possibly not be high enough for all testing requirements.

11.4 Method C: Method using an inverse analysis considering the spatial distribution of the self-demagnetizing field strength in the test specimen

Method C initially assumes a temporary hysteresis loop $J(H)$ and then modifies it so that the calculated demagnetization curve coincides with the measured hysteresis loop $J(H_{\text{ext}})$. This method executes an inverse analysis considering the spatial distribution of the self-demagnetizing field strength in the test specimen using a FEM [9].

Method C does not use the demagnetizing factor N to correct the obtained demagnetization curve $J(H_{\text{ext}})$.

This method assumes the temporary hysteresis loop $J(H)$ as defined in Formula (6). The parameter $\alpha(H)$ shall be corrected in iterations of calculation so that the assumed hysteresis loop $J(H)$ influenced by the self-demagnetizing field strength H_{d} coincides with the measured hysteresis loop $J(H_{\text{ext}})$.

$$J(H) = \gamma \tanh\left(\frac{H - \beta}{1 - \alpha(H)}\right) + (H - \beta)(1 + 0,1\alpha(H)) \quad (6)$$

where

J is the magnetic polarization, in T;

H is the magnetic field strength, in A/m;

$\alpha(H)$ is a parameter as a function of H ;

β and γ are parameters.

Based on the assumed hysteresis loop $J(H)$ defined in Formula (6), the distribution of the self-demagnetizing field strength and local hysteresis loops $J(H)$ in cells of the magnet model shall be calculated using a FEM. Then, parameters $\alpha(H)$, β and γ in Formula (6) shall be modified by comparing the calculated hysteresis loop $J(H_{\text{eff}})$ and the measured hysteresis loop $J(H_{\text{ext}})$. For the conceptual diagram of the procedure of this method, see Figure B.2.

Such operations shall be repeated until the difference between those hysteresis loops becomes smaller than 5 %. If this condition is satisfied, the calculated hysteresis loop $J(H_{\text{eff}})$ can be considered as the corrected demagnetization curve. For the detailed algorithm, see Annex B.

12 Determination of principal magnetic properties

12.1 Remanent magnetic polarization J_r

The remanent magnetic polarization J_r shall be given by the intercept of the corrected demagnetization curve $J(H_{\text{eff}})$ with the J axis ($H_{\text{eff}} = 0$).

NOTE The remanent magnetic polarization has the same value as the remanent flux density.

12.2 Maximum energy product $(BH)_{\text{max}}$

The maximum energy product $(BH)_{\text{max}}$ is the maximum value of the modulus of the product of corresponding values of B and H_{eff} on the demagnetization curve $B(H_{\text{eff}})$.

The demagnetization curve $B(H_{\text{eff}})$ shall be calculated from Formula (7) using the corrected demagnetization curve $J(H_{\text{eff}})$.

$$B = J + \mu_0 H_{\text{eff}} \quad (7)$$

where

B is the magnetic flux density, in T;

J is the magnetic polarization, in T;

μ_0 is the magnetic constant, in H/m; $\mu_0 \cong 4 \pi \times 10^{-7}$;

H_{eff} is the effective magnetic field strength, in A/m.

12.3 Coercivity (H_{cJ} and H_{cB})

The coercivity H_{cJ} shall be given by the intercept of the corrected demagnetization curve $J(H_{\text{eff}})$ with the H axis ($J = 0$).

The coercivity H_{cB} shall be given by the intercept of the demagnetization curve $B(H_{\text{eff}})$ with the H axis ($B = 0$).

13 Reproducibility of the measurements

The reproducibility of the measurements of J_r , H_{cJ} and $(BH)_{\text{max}}$ using the methods defined above is characterized by a relative standard deviation of 1 % or less, 1 % or less and 1,5 % or less, respectively. This reproducibility value has been estimated on the basis of the results of the international round robin test [1], [2].

NOTE The reproducibility of the measurements is equivalent to that of IEC 60404-5.

14 Test report

The test report shall contain the following, as applicable:

- a) the type and condition of the test specimen;
- b) the shape, dimension and volume of the test specimen;
- c) the temperature of the test specimen during measurement;
- d) the method of initial magnetization to saturation;
- e) the measuring method of the magnetic dipole moment;
- f) the type of magnetic dipole moment detection coil (M coil);
- g) the speed of variation of the magnetic field strength during the measurement;
- h) the method of demagnetizing field correction;
- i) the obtained demagnetization curve;
- j) the corrected demagnetization curve;
- k) the saturation magnetic polarization J_s ;
- l) the remanent magnetic polarization J_r ;
- m) the coercivity (H_{cJ} and H_{cB});
- n) the maximum energy product $(BH)_{\max}$;
- o) the values of B and H for $(BH)_{\max}$;
- p) in the case of anisotropic material: the angle of magnetization with respect to the preferred axis of the material if this angle differs from 0° ;
- q) the estimated uncertainty of the measurement.

Annex A (informative)

Demagnetizing field correction

Annex A describes the features of the demagnetizing field correction described in 11.1.

Figure A.1 illustrates a schematic diagram of the demagnetizing field correction. The demagnetizing field correction converts the obtained demagnetization curve $J(H_{\text{ext}})$ into the intrinsic demagnetization curve $J(H_{\text{eff}})$.

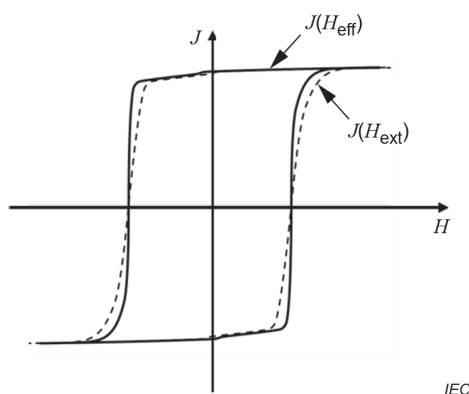


Figure A.1 – Schematic diagram of the demagnetizing field correction

There are three methods of the demagnetizing field correction (see Clause 11):

- Method A: the method using a demagnetizing factor determined by the shape of the test specimen only;
- Method B: the method using a demagnetizing factor determined by the shape and the magnetic susceptibility of the test specimen;
- Method C: the method using an inverse analysis considering the spatial distribution of the self-demagnetizing field strength in the test specimen.

NOTE 1 In the case of an open magnetic circuit, the self-demagnetizing field generated in the test specimen is generally distributed spatially. In the case there is a need for an accurate squareness of the demagnetization curve, Method C is the better method for high accuracy of squareness evaluation, since this method simulates the actual distribution of the self-demagnetizing field strength.

Table A.1 compares features of Method A, Method B and Method C for the correction accuracy and the calculation time. The correction accuracy is evaluated as the difference between the corrected demagnetization curve and the demagnetization curve measured by means of a permeameter in accordance with IEC 60404-5.

Table A.1 – Features of the demagnetizing field correction methods in comparison with Method B

	Method A	Method B	Method C
Correction accuracy	not high	(reference)	sufficiently high
Calculation time	shorter	(reference)	longer

NOTE 2 These methods are applicable to the demagnetization curve obtained by the pulsed field magnetometer (PFM) method. In the PFM method, corrections of the eddy currents in the test specimen and the magnetic viscosity of the permanent magnet material will be applied to the obtained demagnetization curve in addition to the demagnetizing field correction (See IEC TR 62331:2005, 7.1.6.[3]).