IEC 60404-18

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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

IEC 60404-18:2025-02(en-fr)

IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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

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.

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

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

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

- reconfirmed,
- withdrawn, or
- revised.

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

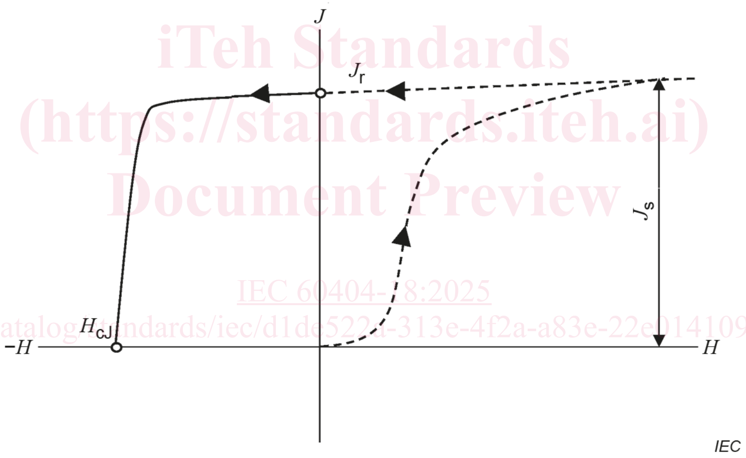
3.1 Terms and definitions

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.

ISO and IEC maintain terminology 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
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

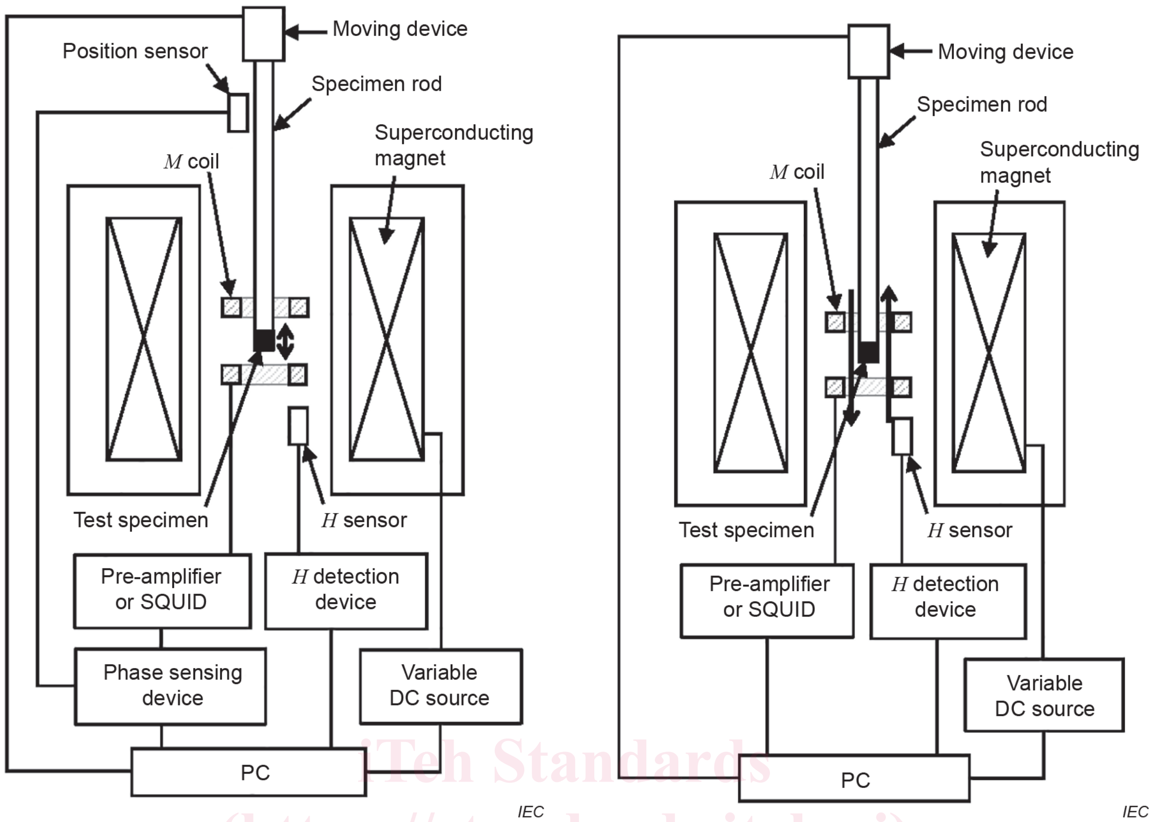
4 General principle

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.



a) **The SCM-VSM method** b) **The SCM-Extraction method**

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 ± 5) °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 ±1 °C in the range between 19 °C and 27 °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 %.

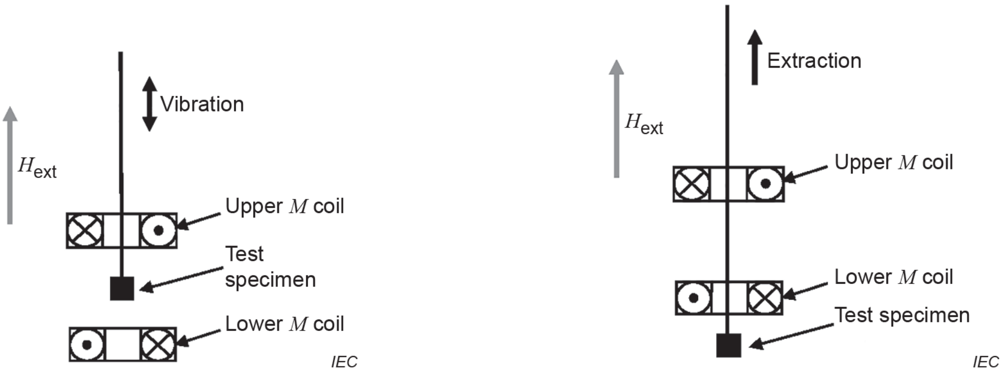
4.4 Magnetic dipole moment detection coil (M coil)

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 ±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].



a) The SCM-VSM method **b) The SCM-Extraction method**

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.