IEC TR 63304

Edition 1.0 2021-04

TECHNICAL REPORT

Methods of measurement of the magnetic properties of permanent magnet (magnetically hard) materials in an open magnetic circuit using a superconducting magnet

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 17.220.20; 29.030

ISBN 978-2-8322-9714-8

Warning! Make sure that you obtained this publication from an authorized distributor.

® Registered trademark of the International Electrotechnical Commission

CONTENTS

FOREWORD 5
INTRODUCTION 7
1 Scope 9
2 Normative references 9
3 Terms and definitions 9
4 General principle 11
4.1 Principle of the method 11
4.2 Superconducting magnet (SCM) 12
4.3 Magnetic field strength sensor (H sensor) 13
4.4 Magnetic dipole moment detection coil (M coil) 13
4.5 Specimen rod and moving device 14
4.6 Measuring devices and the data processing device 14
5 Test specimen 14
6 Preparation of measurement 15
6.1 Measurement of volume of the test specimen 15
6.2 Initial magnetization of the test specimen to saturation 15
7 Determination of magnetic polarization 15
7.1 Measurement of the magnetic dipole moment 15
7.2 Determination of magnetic polarization 16
8 Measurement of magnetic field 17
9 Calibration of the magnetic dipole moment detection coil (M coil) 17
10 Determination of demagnetization curve 17
11 Demagnetizing field correction 18
11.1 General 18
11.2 Method A: Method using a demagnetizing factor determined by the shape of the test specimen only 20
11.3 Method B: Method using a demagnetizing factor determined by the shape and the magnetic susceptibility of the test specimen 20
11.4 Method C: Method using an inverse analysis considering the spatial distribution of the self-demagnetizing field strength in the test specimen 21
12 Determination of principal magnetic properties 21
12.1 Remanent magnetic polarization J_r 21
12.2 Maximum energy product $(BH)_{max}$ 22
12.3 Coercivity (H_{cJ} and H_{cB}) 22
13 Reproducibility 22
14 Test report 22
Annex A (informative) SCM-Magnetometer method 24
Annex B (informative) Effects of the test specimen dimensions 26
Annex C (informative) Superconducting magnets (SCMs) 27
Annex D (informative) Magnetic dipole moment detection coils (M coils) 29
Annex E (informative/normative) Details of the demagnetizing field correction 31
E.1 General 31
E.2 Symbols 31

E.3 Method using a demagnetizing factor determined by the shape and magnetic susceptibility of the test specimen (Method B) 32
E.4 Method using an inverse analysis considering the spatial distribution of the self-demagnetizing field strength in the test specimen (Method C) 34
Annex F (informative) Result of the international round robin test of magnetic properties of permanent magnets using the SCM-VSM and SCM-Extraction methods 39
F.1 General 39
F.2 Protocol of the RRT 39
F.3 Result of the RRT 40
F.4 Reproducibility of the measurements 43
Bibliography 45

Figure 1 – Demagnetization curve $J(H)$ 10
Figure 2 – Schematic diagrams of the test apparatus 11
Figure 3 – Schematic diagrams of the first order gradiometer coil 13
Figure 4 – Relationship between magnetic polarization and self-demagnetizing field 18
Figure 5 – Schematic diagram of the demagnetizing field correction 19
Figure 6 – Conceptual diagram of the procedure of Method C 21
Figure A.1 – Schematic diagram of the test apparatus for the SCM-Magnetometer method 24
Figure A.2 – Schematic diagrams of the test apparatus for the method in a closed magnetic circuit in accordance with IEC 60404-5 25
Figure B.1 – Effects of test specimen dimensions on magnetic properties [B_r, H_cJ, H_cB and $(BH)_\mathrm{max}$] for Nd-Fe-B sintered magnets with different coercivities 26
Figure C.1 – Typical cross-sectional structure of the ceramic SCM 28
Figure D.1 – Schematic diagram of the second order gradiometer coil for the SCM-VSM method 29
Figure D.2 – Schematic diagram of the dependence of induced voltage on the position of the test specimen in the SCM-Extraction method 30
Figure E.1 – Axes of a cuboid magnet 32
Figure E.2 – Conceptual diagram of the procedure of Method C 35
Figure E.3 – Flowchart of the procedure of Method C 36
Figure E.4 – Comparison of the demagnetization curves corrected using demagnetizing field correction Methods A, B and C 38
Figure F.1 – Comparison of J_r measured by the laboratories 40
Figure F.2 – Comparison of H_cJ measured by the laboratories 41
Figure F.3 – Comparison of $(BH)_\mathrm{max}$ measured by the laboratories 41
Figure F.4 – Comparison of hysteresis loops measured by the laboratories 43
Figure F.5 – Relative standard deviation of J_r, H_cJ and $(BH)_\mathrm{max}$ 44

Table 1 – Features of the demagnetizing field correction methods in comparison with Method B 20
Table 2 – Reproducibility of the magnetic properties 22

Table C.1 – Performance of SCMs 27
Table F.1 – Nominal values of coercivity 39
Table F.2 – Participating laboratories and their employed measuring methods 40
Table F.3 – Comparison of magnetic properties measured by the laboratories 42
Table F.4 – Comparison of the reproducibility 44

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

METHODS OF MEASUREMENT OF THE MAGNETIC PROPERTIES OF PERMANENT MAGNET (MAGNETICALLY HARD) MATERIALS IN AN OPEN MAGNETIC CIRCUIT USING A SUPERCONDUCTING MAGNET

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.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TR 63304 has been prepared by IEC technical committee 68: Magnetic alloys and steels. It is a Technical Report.

The text of this Technical Report is based on the following documents:

DTR	Report on voting
68/675/DTR	68/680/RVDTR

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 Technical Report 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/standardsdev/publications.

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

Permanent magnet materials with high coercivity e.g. Nd-Fe-B magnets, have been used in industry and its usage increases rapidly to meet demands to improve energy saving and to increase efficiency of electromagnetic applications, e.g. traction motors for Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV).

However, there is no standard method which can determine all the magnetic properties of the permanent magnet materials with coercivity H_{cJ} higher than 2 MA/m. 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} ≥ 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 using a superconducting magnet (SCM) without a yoke have been developed. The methods using a SCM have been considered to be candidates for solution to accurate measurement of high performance permanent magnets.

The method using a conventional SCM made of metallic superconducting coil has not been used widely for industrial applications due to costs for using expensive liquid helium, limited speed of variation of magnetic field strength, and the difficulty to deal with test specimens of industrial size.

However, nowadays these problems have been solved thanks to the development of a ceramic SCM made of ceramic high temperature superconducting coil. This method has enabled the higher speed of variation of magnetic field strength without using precious resource of liquid helium (see Annex C). Furthermore, test apparatus using the ceramic SCM which can treat test specimens of industrial size have been commercialized globally for industrial use.

However, results of measurement in an open magnetic circuit are different from those of measurement in accordance with IEC 60404-5, particularly in terms of the squareness of demagnetization curves. This is caused by the influence of the self-demagnetizing field in the test specimen, which is opposed to magnetization. This is particular to the measurement in an open magnetic circuit. Therefore, a correction of the influence of self-demagnetizing field (demagnetizing field correction) on the demagnetization curve measured in an open magnetic circuit is indispensable.

This document describes three methods of measurement in an open magnetic circuit using a superconducting magnet (SCM), as follows:

a) SCM-Vibrating Sample Magnetometer (VSM) method;

b) SCM-Extraction method;

c) SCM-Magnetometer method.

In these methods, a test specimen is placed in a detection coil placed in a uniform magnetic field generated by a SCM. For methods a) and b), the magnetic dipole moment of the test specimen is detected by voltage induced in the detection coil due to a vibration and an extraction of the test specimen, respectively. For the method c), a variation of magnetic polarization of a stationary test specimen is detected by voltage induced in the detection coil due to a variation of the magnetic field strength applied to the test specimen.

The reproducibility of measurements of the methods a) and b) has been confirmed by an international round robin test (RRT) that was comparable with that of IEC 60404-5 (see Annex F). However, the reproducibility of the method c) has not been confirmed by a RRT yet. Therefore, the method c) is described separately in Annex A.

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 [1][1]. The PFM is different from the methods described in this document. The PFM measures a steep AC magnetic response of a test specimen in a pulsed current magnetic field. Consequently, additional correction is indispensable due to the influence of eddy currents in the test specimen and the magnetic viscosity of the magnetic materials.

A demagnetization curve should be measured by decreasing the magnetic field strength with a sufficiently slow speed during the reversal of the polarization to avoid significant magnetic viscosity and eddy current effects in accordance with IEC 60404-5. In the case of adopting a conventional metallic SCM made of metallic superconducting coil, the speed of variation of the magnetic field is too slow so that it takes an hour to obtain a demagnetization curve because of a limit of variation rate of the magnetic field to maintain the coil in a superconducting state. The problem has been solved by adopting a newly developed ceramic SCM made of ceramic high temperature superconducting coil so that a demagnetization curve can be measured within several minutes (see Annex C).

A new method of the demagnetizing field correction has been developed (see Annex E). It is a finite element method (FEM) considering the spatial distribution of self-demagnetizing field strength in the test specimen. The squareness of the corrected demagnetization curve is comparable with that measured in accordance with IEC 60404-5.

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

METHODS OF MEASUREMENT OF THE MAGNETIC PROPERTIES OF PERMANENT MAGNET (MAGNETICALLY HARD) MATERIALS IN AN OPEN MAGNETIC CIRCUIT USING A SUPERCONDUCTING MAGNET

1 Scope

This Technical Report describes 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 describes methods to correct the influence of the self-demagnetizing field in the test specimen on the demagnetization curve measured in an open magnetic circuit. The magnetic properties are determined from the corrected demagnetization curve.

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

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 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 – Magnetically hard materials*

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

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

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