

Superconductivity —

Part 2: Critical current measurement — DC critical current of Nb₃Sn composite superconductors

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National foreword

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A list of organizations represented on L/-/90 can be obtained on request to its secretary.

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Foreword

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This European Standard supersedes EN 61788-2:1999.

Modifications made to EN 61788-2:1999 are mostly wording that essentially includes no technical changes and an addition of a new annex (normative Annex D) in which the specifications in the one-mandrel method are described.

The following dates were fixed:

- | | | |
|--|-------|------------|
| – latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement | (dop) | 2007-09-01 |
| – latest date by which the national standards conflicting with the EN have to be withdrawn | (dow) | 2009-12-01 |

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 61788-2:2006 was approved by CENELEC as a European Standard without any modification.

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INTRODUCTION

The critical currents of composite superconductors are used to establish design limits for applications of superconducting wires. The operating conditions of superconductors in these applications determine much of their behaviour and tests made with the method given in the present standard may be used to provide part of the information needed to determine the suitability of a specific superconductor.

Results obtained from this method may also be used for detecting changes in the superconducting properties of a composite superconductor due to processing variables, handling, ageing or other applications or environmental conditions. This method is useful for quality control, acceptance or research testing if the precautions given in this standard are observed.

The critical current of composite superconductors depends on many variables. These variables need to be considered in both the testing and the application of these materials. Test conditions such as magnetic field, temperature and relative orientation of the specimen, current and magnetic field are determined by the particular application. The test configuration may be determined by the particular conductor through certain tolerances. The specific critical current criterion may be determined by the particular application. It may be appropriate to measure a number of test specimens if there are irregularities in testing.

The test method covered in this standard is based on that for the determination of the critical current of Cu/Nb-Ti composite superconductors (IEC 61788-1[2] ¹⁾ and the VAMAS (Versailles project on advanced materials and standards) prestandardization work on the critical current of Nb₃Sn composite superconductors. The critical current of Nb₃Sn superconductors is known to be highly sensitive to mechanical strain compared to Cu/Nb-Ti superconductors. Hence, some modifications are made on the test procedures which may affect the strain state of a test specimen. See Annex B for the background to these modifications.

1) Figures in square brackets refer to the Bibliography.

SUPERCONDUCTIVITY –

Part 2: Critical current measurement – DC critical current of Nb₃Sn composite superconductors

1 Scope

This part of IEC 61788 covers a test method for the determination of the d.c. critical current of Nb₃Sn composite superconductors which are fabricated by either the bronze process or the internal tin diffusion process and have a copper/non-copper ratio larger than 0,2.

This method is intended for use with superconductors which have critical currents of less than 1 000 A and n -values larger than 12 under standard test conditions and at magnetic fields of less than or equal to 0,7 times the upper critical magnetic field. The test specimen is immersed in a liquid helium bath at a known temperature during testing. The Nb₃Sn composite test conductor has a monolithic structure with a total round-cross-sectional area that is less than 2 mm². The specimen geometry used in this test method is an inductively coiled specimen. Deviations from this test method which are allowed for routine tests and other specific restrictions are given in this standard.

Nb₃Sn conductors with critical currents above 1 000 A or total cross-sectional areas greater than 2 mm² can be measured with the present method with an anticipated reduction in precision and a more significant self-field effect (see Annex C). Other, more specialized, specimen test geometries may be more appropriate for larger conductor testing which have been omitted from this present standard for simplicity and to retain precision.

The test method given in this standard should in principle apply to Nb₃Sn composite wires fabricated by any other process. This method is also expected to apply to other superconducting composite wires after some appropriate modifications.

2 Normative references

The following referenced document is indispensable for the application 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 60050-815:2000, *International Electrotechnical Vocabulary (IEV) – Part 815: Superconductivity*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-815, some of which are repeated here for convenience, and the following apply:

3.1 critical current

I_c
maximum direct current that can be regarded as flowing without resistance

NOTE I_c is a function of magnetic field strength and temperature.

[IEV 815-03-01]

3.2 critical current criterion

I_c criterion
criterion to determine the critical current, I_c , based on the electric field strength, E , or the resistivity, ρ

NOTE $E = 10 \mu\text{V/m}$ or $E = 100 \mu\text{V/m}$ is often used as the electric field strength criterion, and $\rho = 10^{-13} \Omega \cdot \text{m}$ or $\rho = 10^{-14} \Omega \cdot \text{m}$ is often used as the resistivity criterion.

[IEV 815-03-02]

3.3 n -value (of a superconductor)

exponent obtained in a specific range of electric field strength or resistivity when the voltage (U) – current (I) curve is approximated by the equation $U \propto I^n$

[IEV 815-03-10]

3.4 quench

uncontrollable and irreversible transition of a superconductor or a superconducting device from the superconducting state to the normal state

NOTE A term usually applied to superconducting magnets.

[IEV 815-03-11]

3.5 Lorentz force (on fluxons)

force applied to fluxons by a current

NOTE 1 The force per unit volume is given by $J \times B$, where J is the current density, and B is the magnetic flux density.

[IEV 815-03-16]

NOTE 2 "Coulomb-Lorentz force" is defined in IEC 121-11-20 [1].

3.6 stress effect strain effect

change in superconducting properties upon application of mechanical, thermal or electromagnetic stress to the superconductor

[IEV 815-03-14]

3.7

bending strain

ε_b

strain in percent arising from pure bending defined as $\varepsilon_b = 100r/R$, where r is a half of the specimen thickness and R is the bending radius

[IEV 815-08-03]

3.8

current transfer (of composite superconductor)

phenomenon that a d.c. current transfers spatially from filament to filament in a composite superconductor, resulting in a voltage generation along the conductor

NOTE In the I_c measurement, this phenomenon appears typically near the current contacts where the injected current flows along the conductor from periphery to inside until uniform distribution among filaments is accomplished.

3.9

constant sweep rate method

U - I data acquisition method where a current is swept at a constant rate from zero to a current above I_c while frequently and periodically acquiring U - I data

3.10

ramp-and-hold method

U - I data acquisition method where a current is ramped to a number of appropriately distributed points along the U - I curve and held constant at each one of these points while acquiring a number of voltages and current readings

4 Principle

The critical current of a composite superconductor is determined from a voltage (U) – current (I) characteristic measured at a certain value of a static applied magnetic field strength (magnetic field) at a specified temperature in a liquid helium bath at a constant pressure. To get a U - I characteristic, a direct current is applied to the superconductor specimen and the voltage generated along a section of the specimen is measured. The current is increased from zero and the U - I characteristic generated is recorded. The critical current is determined as the current at which a specific electric field strength (electric field) criterion (E_c) or resistivity criterion (ρ_c) is reached. For either E_c or ρ_c , there is a corresponding voltage criterion (U_c) for a specified voltage tap separation.

5 Requirements

The specimen shall be wound on a cylindrical reaction mandrel with a helical groove and after reaction, transferred to a measurement mandrel of the same diameter on which the helical angle is preserved. An alternate one-mandrel method is given in Annex D.

The specimen shall be longer than 430 mm.

The specimen shall be affixed to the measurement mandrel by tightening the specimen and/or bonding with a low temperature adhesive.

In this test method, the applied magnetic field shall be parallel to the measurement mandrel axis.

The target precision of this method is a coefficient of variation (standard deviation divided by the average of the critical current determinations), that is less than 3 % for the measurement at 12 T and near 4,2 K.

The use of a common current transfer correction is excluded from this test method. Furthermore, if a current transfer signature is pronounced in the measurement, then the measurement shall be considered invalid.

It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices, and determine the applicability of regulatory limitations prior to use. Specific precautionary statements are given below.

Hazards exist in this type of measurement. Very large direct currents with very low voltages do not necessarily provide a direct personal hazard, but accidental shorting of the leads with another conductor, such as tools or transfer lines, can release significant amounts of energy and cause arcs or burns. It is imperative to isolate and protect current leads from shorting. Also, the stored energy in the superconducting magnets commonly used for the background magnetic field can cause similar large current and/or voltage pulses, or deposit large amounts of thermal energy in the cryogenic systems causing rapid boil-off or even explosive conditions. Under rapid boil-off conditions, cryogenics can create oxygen-deficient conditions in the immediate area and additional ventilation may be necessary. The use of cryogenic liquids is essential to cool the superconductors to allow transition into the superconducting state. Direct contact of skin with cold liquid transfer lines, storage dewars or apparatus components can cause immediate freezing, as can direct contact with a spilled cryogen. It is imperative that safety precautions for handling cryogenic liquids be observed.

6 Apparatus

For the one-mandrel method, continue with Clause D.2.

6.1 Reaction mandrel material

The reaction mandrel shall be made from a heat-resistant material that may or may not have a treated surface. Suitable reaction mandrel materials are recommended in A.3.1. Any one of these may be used.

6.2 Reaction mandrel construction

The overall geometry of the reaction mandrel should be matched closely to that of the measurement mandrel to which the individual specimen is to be transferred.

The reaction mandrel shall have a diameter large enough that the specimen bending strain, which is introduced into the specimen during winding, is less than 5 %.

The mandrel shall have a helical groove in which the specimen shall be wound. The pitch angle of the groove shall be less than 7°. The depth of the groove shall be at least half the wire diameter.

6.3 Measurement mandrel material

The measurement mandrel shall be made from an insulating material, or from a conductive non-ferromagnetic material that is either covered or not covered with an insulating layer.

The critical current may inevitably depend on the measurement mandrel material due to the strain induced by the differential thermal contraction between the specimen and the measurement mandrel.

The total strain induced in the specimen at the measuring temperature shall be minimized to be within $\pm 0,03$ %. If there is an excess strain due to the differential thermal contraction of the specimen and the mandrel, the critical current shall be noted to be determined under an excess strain state by identification of the mandrel material.

Suitable measurement mandrel materials are recommended in A.3.3. Any one of these may be used.

When a conductive material is used without an insulating layer, the leakage current through the mandrel shall be less than 0,2 % of the total current when the specimen current is at critical current I_c (see 9.5).

6.4 Measurement mandrel construction

The mandrel shall have a helical groove in which the specimen shall be wound.

The diameter of the measurement mandrel, the pitch angle of the helical groove and its depth and shape shall be close to those of the reaction mandrel.

The angle between the specimen axis (portion between the voltage taps) and the magnetic field shall be $(90 \pm 7)^\circ$. This angle shall be determined with an accuracy of $\pm 2^\circ$.

The current contact shall be rigidly fastened to the measurement mandrel to avoid stress concentration in the region of transition between the mandrel and the current contact.

6.5 Measurement set up

The apparatus to measure the $U-I$ characteristic of a superconductor specimen consists of a specimen probe, a test cryostat, a magnet system and a $U-I$ measurement system.

The specimen probe, which consists of a specimen, a measurement mandrel, a specimen support structure, voltage taps, current leads etc. is inserted in the test cryostat filled with liquid helium. In most cases, the cryostat contains a superconducting solenoid magnet and its support structure to apply a magnetic field to the specimen. The $U-I$ measurement system consists of a d.c. current source, a recorder and necessary preamplifiers, filters or voltmeters, or a combination thereof. A computer-assisted data acquisition system may be also used.

7 Specimen preparation

For the one-mandrel method, continue with Clause D.4.

7.1 Specimen mounting for reaction heat treatment

There shall be no joints or splices in the test specimen.