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colour inside

Superconductivity –
Part 17: Electronic characteristic measurements – Local critical current density and its distribution in large-area superconducting films

INTERNATIONAL
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SUPERCONDUCTIVITY –

Part 17: Electronic characteristic measurements – Local critical current density and its distribution in large-area superconducting films

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INTRODUCTION

Over thirty years after their discovery in 1986, high-temperature superconductors are now finding their way into products and technologies that will revolutionize information transmission, transportation, and energy. Among them, high-temperature superconducting (HTS) microwave filters, which exploit the extremely low surface resistance of superconductors, have already been commercialized. They have two major advantages over conventional non-superconducting filters, namely: low insertion loss (low noise characteristics) and high frequency selectivity (sharp cut) [1][1]. These advantages enable a reduced number of base stations, improved speech quality, more efficient use of frequency bandwidths, and reduced unnecessary radio wave noise.

Large-area superconducting thin films have been developed for use in microwave devices [2]. They are also ~~used~~ considered for use in emerging superconducting power devices, such as resistive-type superconducting fault-current limiters (SFCLs) [3] [4] [5], superconducting fault detectors used for superconductor-triggered fault current limiters [6] [7] and persistent-current switches used for persistent-current HTS magnets [8] [9]. The critical current density J_c is one of the key parameters that describe the quality of large-area HTS films. Nondestructive, AC inductive methods are widely used to measure J_c and its distribution for large-area HTS films [10] [11] [12] [13], among which the method utilizing third-harmonic voltages $U_3\cos(3\omega t + \theta)$ is the most popular [10] [11], where ω, t and θ denote the angular frequency, time, and initial phase, respectively. However, these conventional methods are not accurate because they have not considered the electric-field E criterion of the J_c measurement [14] [15] and sometimes use an inappropriate criterion to determine the threshold current I_{th} from which J_c is calculated [16]. A conventional method can obtain J_c values that differ from the accurate values by 10 % to 20 % [15]. It is thus ~~necessary~~ important to establish standard test methods to precisely measure the local critical current density and its distribution, to which all involved in the HTS filter industry can refer for quality control of the HTS films. Background knowledge on the inductive J_c measurements of HTS thin films is summarized in Annex A.

In these inductive methods, AC magnetic fields are generated with AC currents $I_0\cos\omega t$ in a small coil mounted just above the film, and J_c is calculated from the threshold coil current I_{th}, at which full penetration of the magnetic field to the film is achieved [17]. For the inductive method using third-harmonic voltages U_3, U_3 is measured as a function of I_0, and the I_{th} is determined as the coil current I_0 at which U_3 starts to emerge. The induced electric fields E in the superconducting film at $I_0 = I_{th}$, which are proportional to the frequency f of the AC current, can be estimated by a simple Bean model [14]. A standard method has been proposed to precisely measure J_c with an electric-field criterion by detecting U_3 and obtaining the n-value (index of the power-law E-J characteristics) by measuring I_{th} precisely at various frequencies [14] [15] [18] [19]. This method not only obtains precise J_c values, but also facilitates the detection of degraded parts in inhomogeneous specimens, because the decline of n-value is more ~~remarkable~~ noticeable than the decrease of J_c in such parts [15]. It is noted that this standard method is excellent for assessing homogeneity in large-area HTS films, although the relevant parameter for designing microwave devices is not J_c, but the surface resistance. For application of large-area superconducting thin films to SFCLs, knowledge on J_c distribution is vital, because J_c distribution significantly affects quench distribution in SFCLs during faults.

The International Electrotechnical Commission (IEC) draws attention to the fact that it is claimed that compliance with this document may involve the use of a patent ~~concerning the determination of the E-J characteristics by inductive J_c measurements as a function of frequency, given in the Introduction, Clause 1, Clause 4 and 5.1~~. IEC takes no position concerning the evidence, validity, and scope of this patent right.

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SUPERCONDUCTIVITY –

Part 17: Electronic characteristic measurements – Local critical current density and its distribution in large-area superconducting films

1 Scope

This part of IEC 61788 ~~describes~~ specifies the measurements of the local critical current density (J_c) and its distribution in large-area high-temperature superconducting (HTS) films by an inductive method using third-harmonic voltages. The most important consideration for precise measurements is to determine J_c at liquid nitrogen temperatures by an electric-field criterion and obtain current-voltage characteristics from its frequency dependence. Although it is possible to measure J_c in applied DC magnetic fields [20] [21], the scope of this document is limited to the measurement without DC magnetic fields.

This technique intrinsically measures the critical sheet current that is the product of J_c and the film thickness d. The range and measurement resolution for $J_c d$ of HTS films are as follows.

– $J_c d$: from 200 A/m to 32 kA/m (based on results, not limitation).

– Measurement resolution: 100 A/m (based on results, not limitation).

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~~IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at http://www.electropedia.org<http://www.electropedia.org>)~~

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Superconductivity –
Part 17: Electronic characteristic measurements – Local critical current density and its distribution in large-area superconducting films

Supraconductivité –
Partie 17: Mesurages de caractéristiques électroniques – Densité de courant critique local et sa distribution dans les films supraconducteurs de grande surface

IEC 61788-17:2021-04(en-fr)

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Partie 17: Mesurages de caractéristiques électroniques – Densité de courant critique local et sa distribution dans les films supraconducteurs de grande surface

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Cette deuxième édition annule et remplace la première édition parue en 2013. Cette édition constitue une révision technique.

Cette édition inclut la modification technique majeure suivante par rapport à l'édition précédente:

a) une méthode simple de calcul du coefficient de bobine théorique k est décrite en 6.2.1.

La présente version bilingue (2021-09) correspond à la version anglaise monolingue publiée en 2021-04.

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INTRODUCTION

Plus de trente ans après avoir été découverts, en 1986, les supraconducteurs à haute température sont désormais utilisés dans des produits et des technologies qui sont appelés à révolutionner la transmission d'informations, le transport et l'énergie. Parmi ces produits, des filtres micro-ondes à supraconducteurs à haute température (HTS – *high-temperature superconducting*) qui exploitent la résistance de surface extrêmement faible des supraconducteurs sont déjà commercialisés. Ils présentent deux avantages majeurs par rapport aux filtres classiques sans supraconducteur, à savoir: un faible affaiblissement d'insertion (caractéristiques de faible bruit) et une grande sélectivité en fréquence (coupure brutale) [1][1]. Ces avantages ont pour conséquence un nombre réduit de stations de base, une amélioration de la qualité de la parole, une utilisation plus efficace des largeurs de bande de fréquence et une diminution du bruit inutile des ondes radio.

Des films minces à supraconducteurs de grande surface ont été réalisés pour être utilisés dans des dispositifs à micro-ondes [2]. Leur utilisation pour les dispositifs de puissance à supraconducteurs émergents, tels que les limiteurs de courant de défaut à supraconducteur de type résistif (SFCL – *superconducting fault-current limiter*) [3] [4] [5], les détecteurs de défaut à supraconducteur utilisés pour les limiteurs de courant de défaut déclenchés par supraconduction [6] [7] et les interrupteurs de courant électrique persistant utilisés pour les aimants HTS à courant persistant [8] [9], est également à l'étude. La densité de courant critique J_c est l'un des paramètres fondamentaux qui décrivent la qualité des films HTS de grande surface. Des méthodes inductives non destructives en courant alternatif sont largement utilisées pour mesurer J_c et sa distribution pour les films HTS de grande surface [10] [11] [12] [13]. Parmi elles, la méthode qui utilise les tensions de troisième harmonique $U_3\cos(3\omega t + \theta)$ est la plus répandue [10] [11], où ω, t et θ représentent respectivement la fréquence angulaire, le temps et la phase initiale. Ces méthodes classiques ne sont toutefois pas exactes, car elles ne prennent pas en considération le critère de champ électrique E du mesurage de J_c [14] [15] et utilisent parfois un critère inapproprié pour déterminer le courant de seuil I_{th} d'après lequel est calculée J_c [16]. Une méthode classique permet d'obtenir des valeurs de J_c qui diffèrent de 10 % à 20 % des valeurs exactes [15]. Il est donc important de déterminer des méthodes d'essai normalisées pour mesurer précisément la densité de courant critique local et sa distribution, auxquelles peut se référer tout ce qui concerne l'industrie des filtres HTS pour le contrôle de la qualité des films HTS. Les connaissances acquises dans le domaine des mesurages inductifs de J_c des films HTS minces sont résumées à l'Annexe A.

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1 Les chiffres entre crochets se réfèrent à la Bibliographie.

Dans ces méthodes inductives, des champs magnétiques en courant alternatif sont générés avec des courants alternatifs $I_0\cos\omega t$ dans une petite bobine montée juste au-dessus du film et J_c est calculée d'après le courant de seuil de la bobine I_{th}, pour lequel une pénétration complète du champ magnétique dans le film [17] est obtenue. En ce qui concerne la méthode inductive qui utilise les tensions de troisième harmonique U_3, U_3 est mesurée en fonction de I_0, et I_{th} est déterminé en tant que courant de bobine I_0 auquel U_3 commence à apparaître. Les champs électriques induits E dans le film supraconducteur à $I_0 = I_{th}$, qui sont proportionnels à la fréquence f du courant alternatif, peuvent être estimés par un simple modèle de Bean [14]. Une méthode normalisée a été proposée pour mesurer précisément J_c avec un critère de champ électrique par détection de U_3 et obtention de la valeur n (indice des caractéristiques de la loi de puissance E-J) par un mesurage précis de I_{th} à différentes fréquences [14] [15] [18] [19]. Non seulement cette méthode permet d'obtenir des valeurs précises de J_c, mais elle facilite également la détection des parties dégradées dans des éprouvettes inhomogènes, car la diminution de la valeur n est plus remarquable que la diminution de J_c dans ces parties [15]. Noter que cette méthode normalisée est excellente pour évaluer l'homogénéité dans des films HTS de grande surface, bien que le paramètre approprié pour concevoir des dispositifs à micro-ondes ne soit pas J_c, mais la résistance surfacique. Pour une application de films minces supraconducteurs de grande surface à des SFCL, la connaissance de la distribution de J_c est fondamentale, car la distribution de J_c a une influence significative sur la distribution de l'extinction dans les SFCL en cas de défaut.

La Commission électrotechnique internationale (IEC) attire l'attention sur le fait qu'il est déclaré que la conformité avec les dispositions du présent document peut impliquer l'utilisation d'un brevet. L'IEC ne prend pas position quant à la preuve, à la validité et à la portée de ces droits de propriété.

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L'attention est d'autre part attirée sur le fait que certains des éléments du présent document peuvent faire l'objet de droits de propriété autres que ceux contenus dans la base de données des droits de propriété. L'IEC ne saurait être tenue pour responsable de ne pas avoir identifié de tels droits de propriété et de ne pas avoir signalé leur existence.

SUPRACONDUCTIVITÉ –

Partie 17: Mesurages de caractéristiques électroniques – Densité de courant critique local et sa distribution dans les films supraconducteurs de grande surface

1 Domaine d'application

La présente partie de l'IEC 61788 spécifie les mesurages de la densité de courant critique local (J_c) et sa distribution dans les films supraconducteurs à haute température (HTS) de grande surface par une méthode inductive qui utilise les tensions de troisième harmonique. Le plus important, pour effectuer des mesurages précis, est de déterminer J_c aux températures de l'azote liquide au moyen d'un critère de champ électrique et obtenir des caractéristiques courant-tension d'après sa dépendance vis-à-vis de la fréquence. Bien qu'il soit possible de mesurer J_c dans des champs magnétiques en courant continu appliqués [20] [21], le domaine d'application du présent document est limité au mesurage sans champ magnétique en courant continu.

Cette technique mesure de façon intrinsèque le courant de feuille critique, qui est le produit de J_c par l'épaisseur d du film. La plage et la résolution de mesure pour J_cd des films HTS sont les suivantes:

– J_cd: de 200 A/m à 32 kA/m (sur la base de résultats, aucune limitation).
– Résolution de mesure: 100 A/m (sur la base de résultats, aucune limitation).

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 60050-815, *Vocabulaire Électrotechnique International – Partie 815: Supraconductivité* (disponible à l'adresse: <http://www.electropedia.org>)