



**HAL**  
open science

## Test Station for High Temperature Superconducting Power Cables

Loïc Quéval, Damien Huchet, Frédéric Trillaud, M. Kiuchi, T. Matsushita

► **To cite this version:**

Loïc Quéval, Damien Huchet, Frédéric Trillaud, M. Kiuchi, T. Matsushita. Test Station for High Temperature Superconducting Power Cables. IEEE Transactions on Applied Superconductivity, 2024, 34 (3), pp.1-4. 10.1109/TASC.2024.3360931 . hal-04404432

**HAL Id: hal-04404432**

**<https://hal.science/hal-04404432v1>**

Submitted on 16 Jan 2025

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Author's post-print (ie final draft post-refereeing) published in the IEEE Transactions on Applied Superconductivity (May 2024).

©2024 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works.

DOI: <http://doi.org/10.1109/TASC.2024.3360931>

URL: <https://ieeexplore.ieee.org/document/10418537>

Cite: L. Quéval, D. Huchet, F. Trillaud, M. Kiuchi, T. Matsushita, "Test station for high temperature superconducting power cables," IEEE Transactions on Applied Superconductivity, vol. 34, no. 3, pp. 1-4, May. 2024.

# Test Station for High Temperature Superconducting Power Cables

L. Quéval<sup>1,2</sup>, D. Huchet<sup>1,2</sup>, F. Trillaud<sup>3</sup>, M. Kiuchi<sup>4</sup>, T. Matsushita<sup>4</sup>

<sup>1</sup>Université Paris-Saclay, CentraleSupélec, CNRS, Laboratoire de Génie électrique et Electrotechnique de Paris, 91190 Gif-sur-Yvette, France. <sup>2</sup>Sorbonne Université, CNRS, Laboratoire de Génie Electrique et Electrotechnique de Paris, 75252 Paris, France. <sup>3</sup>Instituto de Ingeniería, Universidad Nacional Autónoma de Mexico, 04510 Ciudad de Mexico, México. <sup>4</sup>Kyushu Institute of Technology, Iizuka, Fukuoka 820-8502, Japan

**Abstract**—The Gargantua test station is capable of delivering a direct current of 4800 A at a voltage of 10 V. It is designed for acquiring the DC voltage-current characteristic of high-temperature superconducting power cables operating at 77.3 K in liquid nitrogen. The goal is to estimate their critical current. The standardization of this DC characterization is a prerequisite for the adoption of this promising technology by power grid operators. This document reports on the experimental setup and the subsequent measurements carried out on a high-temperature superconducting power cable manufactured by Sumitomo and tested as part of the international round robin test for the IEC Technical Committee 90 Superconductivity.

**Index Terms**—high current, superconducting power cable, voltage-current characteristic, standardization.

## I. INTRODUCTION

Despite various successful demonstration projects, including continuous in-grid operation [1], high-temperature superconducting (HTS) power cable systems are still considered as "lacking of maturity". One of the reasons slowing down the adoption process is the absence of standard for HTS power cable and their accessories. Indeed, without standard, the large scale adoption of a technology is unlikely.

The community is strongly involved in this standardization work. In 2013, the CIGRE Working Group B1.31 published recommendations for the testing of AC HTS cables, including the measurement of their critical current [2]. In 2019, the International Electrotechnical Commission (IEC) published an international standard on the test methods and requirements for AC HTS power cables [3]. Recently, as part of a three-year national project (2018-2020), Japan has initiated a national round robin test campaign [4]. The aim of this campaign is to enable different industrial and academic groups to characterize the same HTS cable, to compare their methods and results, and to converge towards a standard for the measurement of the critical current [5]. The tests were carried out for short single-core Bi-2223 cables, >1 m in length, operated in liquid nitrogen at 77.3 K with a critical current below 10 kA. Coordinated by Japan, this round robin test campaign has recently been extended internationally through the IEC Technical Committee 90 (TC90) Superconductivity, and now involves several groups around the world. It is still a work in progress despite [6]. With the support of the French Organization for Standardization (AFNOR/UF TC90), we joined this round robin test campaign

in 2021. Since then, Gargantua, a test station for HTS power cables has been developed and is now fully operational.

The aim of this article is twofold. Firstly, the test station is described. Secondly, the tests carried out for the international round robin test are reported.



Fig. 1. Overview of the 4800 A Gargantua test station for acquiring the  $V$ - $I$  characteristic of HTS power cables at 77.3 K in liquid nitrogen.

## II. OVERVIEW OF THE TEST STATION

In this section, the test station for HTS cables, named Gargantua, is detailed. It has been developed by the superconductivity group of the laboratory GeePs (Group of Electricity and Electronics of Paris), at CentraleSupélec, University of Paris-Saclay, France. It consists of several elements: DC power supply, busbars, cables/braids, cryostat, profile structures, nanovoltmeter, thermometer, and computer. An overview of the platform is shown in Fig. 1.

The DC power supply consists of 4 identical Sorensen SGX1200 DC power supplies connected in parallel. The master power supply drives 3 slaves to provide the required current (current control mode with voltage sensing at each power supply output). Each power supply delivers 1200 A max at a maximum of 10 V. So the system is capable of delivering 4800 A max at a maximum of 10 V (see Fig. 2a). Two L-shaped aluminum busbars are used for parallel connection

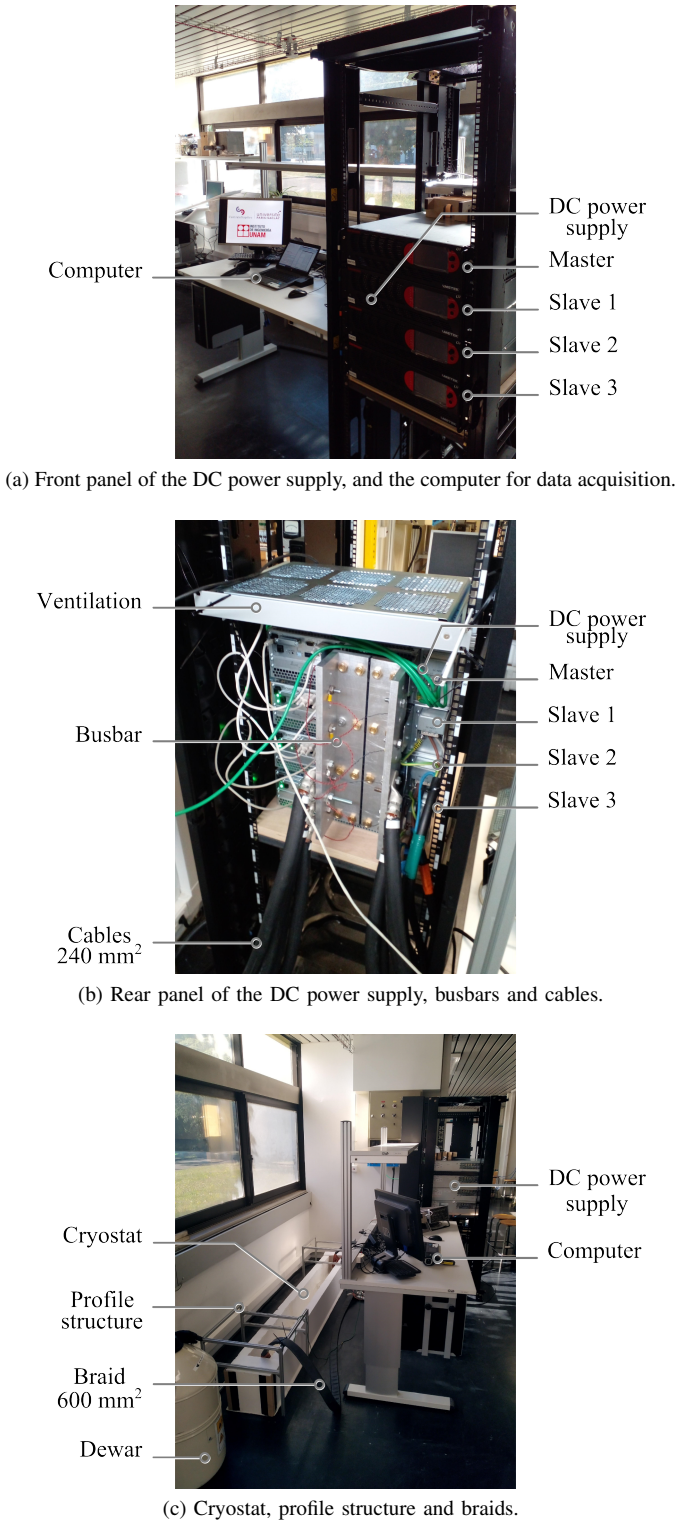


Fig. 2. Details of the 4800 A Gargantua test station.

of the power supplies (see Fig. 2b). They are designed to withstand 4800 A in steady state. To connect the busbars to the HTS cables, a combination of 1.5 m-long 240 mm<sup>2</sup> copper cables and 3 m-long 600 mm<sup>2</sup> copper braids are used. The cryostat was carved in an high-density (30 kg/m<sup>3</sup>) expanded polystyrene (EPS) block. Its external volume is 2500 × 300 × 300 mm. Its internal volume is 2000 × 200 × 150 mm. It can

contain ~40 L of liquid nitrogen (LN2) at ~77.3 K under atmospheric pressure. An aluminum profile support structure surrounds the cryostat on both extremities. This is to hold the copper braids in place to reduce the mechanical forces exerted on the HTS cable connectors, thus avoiding damage to the cable during installation and thermal cycling (see Fig. 2c). To measure low voltages, a Keithley 2182 nanovoltmeter is used. The LN2 bath temperature is measured with a platinum thermocouple via a Graphtec GL 840-WV. A computer is used to control the power supply master via LAN and the nanovoltmeter via RS232. It records the following data: power supply voltage, power supply current, and nanovoltmeter voltage. Data acquisition and processing are managed by a Matlab script. During the test, measurements are displayed in real time on a graphical interface. At the end of the run, all the raw data are automatically saved in a \*.mat file.

### III. DC CHARACTERIZATION OF THE TC90 HTS CABLE

#### A. Overview of the cable

The cable was manufactured by Sumitomo (Fig. 3). It is subsequently denominated “TC90 HTS cable”. It has a length of about 2 m, with two HTS layers wound around a former. The inner layer is the conductor layer transmitting the power. The outer layer is the shield. Very little information has been given to us about the structure of the cable [4]. This is deliberate, as the aim of the round robin test is to characterize an unknown cable whose structure may well be confidential.

The cable is pre-equipped with soldered voltage taps. The voltage taps for the conductor layer are denominated C1 and are spaced 160 cm apart along the cable axis (measured at 169.2 cm). The voltage taps for the shield layer are denominated S1 and are spaced 120 cm apart along the cable axis (measured at 119 cm). We chose to rely on the provided values instead of the measured ones.

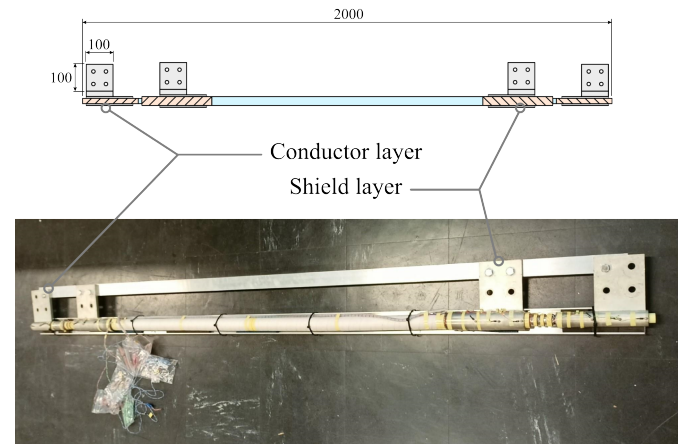


Fig. 3. Overview of the TC90 HTS cable.

#### B. Sequence

To measure the DC voltage-current  $V$ - $I$  characteristic, the current is ramped up from 0 to  $I_{stop}$  in 80 steps. After each step, a 10 s wait is respected to allow the current density

to redistribute in the cable cross section. The nanovoltmeter voltage is then recorded, as well as the power supply output voltage and output current. The nanovoltmeter voltage is averaged over 12 recordings per step to reduce the noise. If the current reaches  $I_{stop}$  or if the tap-to-tap voltage reaches  $V_{stop}$ , the current is automatically ramped down to zero.  $I_{stop}$  is set at 4700 A, an arbitrary value below Gargantua's maximum current.  $V_{stop}$  is set to a multiple of the critical voltage  $V_c$ . By experience, it is possible to measure the voltage up to 3 times  $V_c$  for a BSCCO cable, without risk of damage.  $V_c$  is defined by,

$$V_c = E_c L_{sc} \quad (1)$$

where  $E_c$  is an arbitrary voltage criterion usually set at  $1 \mu\text{V}/\text{cm}$  and  $L_{sc}$  is the mean length of the current path between the voltage taps. Since we have no information on the cable structure,  $L_{sc}$  is set equal to the tap-to-tap distance along the cable axis; the conductor twist pitch is hence neglected. For the conductor layer, the length  $L_{sc}=160 \text{ cm}$  is adopted leading to  $V_c=160 \mu\text{V}$ . For the shield layer,  $L_{sc}=120 \text{ cm}$  is taken leading to  $V_c=120 \mu\text{V}$ .

### C. List of measurements

The first set of tests consists of:

- Hot 1: Measure of the resistance at room temperature, between the voltage taps C1 ( $I_{stop}=100 \text{ A}$ )
- Hot 2: Measure of the resistance at room temperature, between the voltage taps S1 ( $I_{stop}=100 \text{ A}$ )

Then, the conductor is connected to the DC power supply using copper cables/braids, while the shield is left open circuit (Fig. 4). A first cooling is performed. To do this, we gradually fill the cryostat in which the cable rests with LN2 and wait 60 minutes to ensure that the cable is fully cooled to 77.3 K. The 2nd set of tests consists of:

- Cond 1:  $V$ - $I$  characteristic @LN2, between voltage taps C1 ( $V_{stop}=2V_c$  or  $I_{stop}=4700 \text{ A}$ )
- Cond 2:  $V$ - $I$  characteristic @LN2, between voltage taps C1 ( $V_{stop}=3V_c$  or  $I_{stop}=4700 \text{ A}$ )
- Cond 3:  $V$ - $I$  characteristic @LN2, between voltage taps C1 ( $V_{stop}=3V_c$  or  $I_{stop}=4700 \text{ A}$ )

The cable is left to warm up overnight, allowing the LN2 to evaporate. The next morning, the shield is connected to the DC power supply, while the conductor is left open circuit (Fig. 5). A second cooling is performed. The 3rd set of tests consists of:

- Shield 1:  $V$ - $I$  characteristic @LN2, between voltage taps S1 ( $V_{stop}=3V_c$  or  $I_{stop}=4700 \text{ A}$ )
- Shield 2:  $V$ - $I$  characteristic @LN2, between voltage taps S1 ( $V_{stop}=4V_c$  or  $I_{stop}=4700 \text{ A}$ )
- Shield 3:  $V$ - $I$  characteristic @LN2, between voltage taps S1 ( $V_{stop}=4V_c$  or  $I_{stop}=4700 \text{ A}$ )

At the end of the tests, the cable is left to warm up.

### D. Results

From the tests Hot 1 and Hot 2, one can deduce the layer resistances at room temperature (Table I).

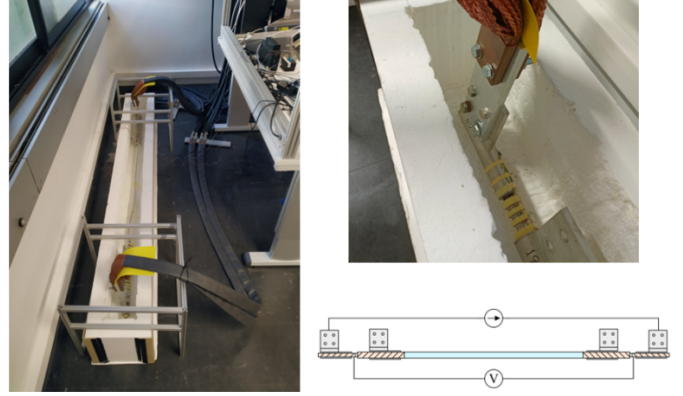


Fig. 4. Setup of the TC90 HTS cable for DC characterization of the conductor layer (C1).

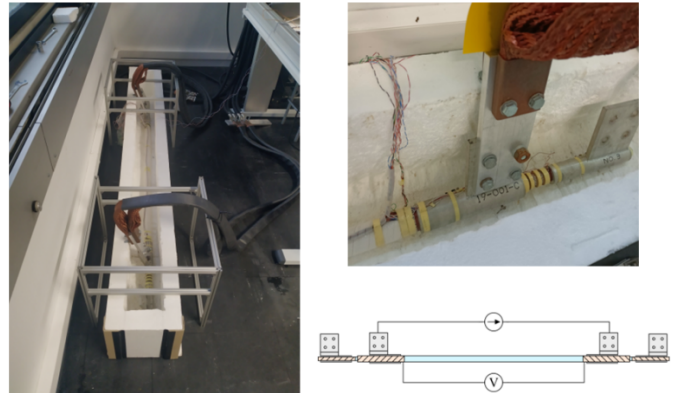


Fig. 5. Setup of the TC90 HTS cable for DC characterization of the shield layer (S1).

TABLE I  
RESULTS OF TESTS HOT 1 AND HOT 2.

Test	Hot 1	Hot 2
$R$ [ $\mu\Omega$ ]	1478	1480

The results of the tests Cond 1, Cond 2 and Cond 3 are shown in Fig. 6. This demonstrates that an excellent reproducibility of the measurement is obtained with the current experimental setup.

The power law is used to fit the measured  $V$ - $I$  characteristic yielding the layer critical current  $I_c$  and power law index  $n$  according to:

$$V_{sc} = V_c \left( \frac{I_{sc}}{I_c} \right)^n \quad (2)$$

where  $V_{sc}$  is the layer tap-to-tap voltage,  $I_{sc}$  is the layer current, and  $V_c$  is the critical voltage defined by (1). In this case,  $L_{sc} = 160 \text{ cm}$  is used. Table II summarizes the results. Note that the voltage for Cond 1 is very slightly higher than Cond 2, which is higher than Cond 3. This leads to a small improvement of  $I_c$  after each test. The cause of this effect needs further investigation.

The results of the tests Shield 1, Shield 2 and Shield 3 are plotted together on Fig. 7. It shows again excellent reproducibility of the measurement. Here too, to estimate the

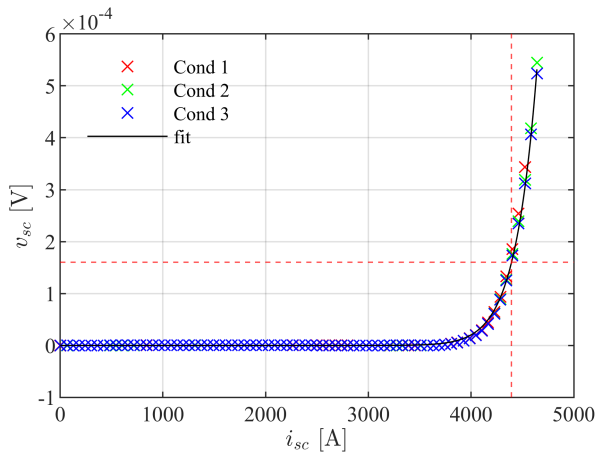


Fig. 6. Results of Cond 1 to Cond 3. The fit is given for Cond 3.

TABLE II  
RESULTS COND 1, COND 2 AND COND 3

Test	Cond 1	Cond 2	Cond 3	Ave / Std
$I_c$ [A]	4380	4389	4393	4387 / 7
$n$ [-]	24.2	22.3	21.9	22.8 / 1.2

critical current and the power law index of the shield layer, the power law is used to fit the measured  $V$ - $I$  characteristic. However here  $L_{sc} = 120$  cm is used. Table III summarizes the results. Here again, a slight improvement of  $I_c$  after each test can be observed.

#### IV. DISCUSSION

During such measurement, the first difficulty that arises is related to the definition of  $L_{sc}$  or  $V_c$ . One could have calculated  $L_{sc}$  using tape length, accounting for the twist angle of the tape around the former. However, we didn't have this information, as can happen in practice. Besides, a conductor is likely to consist of several HTS layers with different twist angles making unpractical to define a given tape length. Not to mention that voltage taps are only connected to the outer layer... The choice of  $L_{sc}$  is then not obvious. In this context, we propose to adopt  $L_{sc}$  as the distance between the voltage taps along the cable axis as a standard. We argue here that this provides a simple solution and consistency across different test facilities. Ultimately, it will always yield a conservative estimation of the critical current.

A second difficulty is related to the choice of the power law to identify the critical current  $I_c$  and the power law index  $n$ . The relevancy and goodness of the fit can be questioned as demonstrated in the shield case for the TC90 HTS cable (Fig. 7). Here a methodology should be worked out to provide a consistent estimation of the basic electrical characteristic  $I_c$  and  $n$  index of cables across test facilities.

A third difficulty is to decide whether to include a thermal cycling or not. Here, we have kept the cable in a cold state for three successive measurements, but an alternative would be to heat the cable between each measurement. This would allow any degradation due to thermal cycling to be taken into account, but it would make testing longer and more costly.

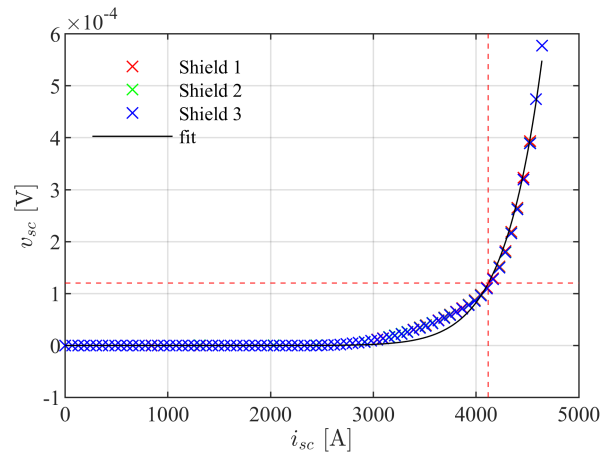


Fig. 7. Results of Shield 1 to Shield 3. The fit is given for Shield 3.

TABLE III  
RESULTS SHIELD 1, SHIELD 2 AND SHIELD 3

Test	Shield 1	Shield 2	Shield 3	Ave / Std
$I_c$ [A]	4088	4117	4118	4108 / 17
$n$ [-]	11.0	12.7	12.7	12.1 / 1.0

#### V. CONCLUSION

Gargantua, a 4800 A test station for the  $V$ - $I$  characterization of HTS power cables was designed, built and tested. A test protocol has been proposed and successfully used to characterize a HTS cable, as part of an IEC TC90 international round robin test organized by Japan. The obtained  $V$ - $I$  characteristics are clean and reproducible. We have discussed some of the difficulties that need to be resolved in order to make progress towards standardizing the measurement of the critical current of a HTS power cable. The definition of such a standard could be the key to the adoption of superconducting technology by power grid operators and its widespread deployment.

#### ACKNOWLEDGMENTS

This work was carried out with the support of the French Organization for Standardization (AFNOR/UF TC90). It also benefited from the financial support of the SuperRail project, funded by the French government as part of the Plan de Relance and the Programme d'investissements d'avenir. F. Trillaud would like to thank the Programa de Apoyos para la Superación del Personal Académico (PASPA) of the Dirección General de Asuntos del Personal Académico (DGAPA) de la UNAM for supporting financially his sabbatical year (2022) under grant PASPA-2022.

#### REFERENCES

- [1] M. Stemmler, K. Allweins, F. Merschel, T. Kugel, F. Herzog, T. Kutz, J.M. Saugrain, "Three years operation experience of the ampacity system installation in essen Germany," *13th European Conference on Applied Superconductivity (EUCAS2017)*, id. 3LO4-05, Geneva, Switzerland, Sep. 2017.
- [2] CIGRE B1, "Recommendations for testing of superconducting cables," Technical brochure, no. 538, Jun. 2013.
- [3] "HTS-AC power cables and their accessories - Test methods and requirements," Standard IEC 63075:2019.

- [4] T. Matsushita *et al.*, "Japanese project of standardization of DC critical current test method of superconducting cables," *14th European Conference on Applied Superconductivity (EUCAS2019)*, id. 1-LP-PC-I05, Glasgow, UK, Sept. 2019.
- [5] T. Matsushita *et al.*, "Round Robin Test of Critical Current of Superconducting Cable," *IEEE Transactions on Applied Superconductivity*, vol. 31, No. 5, pp. 1-4, 2021.
- [6] J. Li *et al.*, "China's participation in the international RRT for  $I_c$  measurement of superconducting cables organized by IEC/TC90," *Superconductivity*, vol. 1, pp. 100004, 2022.
- [7] A. Musso, G. Angeli, M. Bocchi, P.L. Ribani, M. Breschi, "A method to quantify technical-economic aspects of HTS electric power cables," *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 9, id. 4803516, Dec. 2022.
- [8] B. Douine, L. Quéval, F. Trillaud, S. Fawaz, H. Menana, I. Schwenker, O. Despouys, N. Ivanov, "Characterization of a superconducting power filter for embedded electrical grid application," *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 4, Jun. 2022.
- [9] D. Kottonau, E. Shabagin, W.T.B. de Sousa, J. Geisbüsch, M. Noe, H. Stagge, S. Fechner, H. Woiton, T. Küsters, *Bewertung des Einsatzes supraleitender 380-kV-Kabel*, vol. 26. KIT Scientific Publishing, 2019.