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Superconducting high-power cables and lines—development status and technology roadmap

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ROADMAP

Superconducting high-power cables and lines—development status and technology roadmap

M Noe[1,*], T Puig[2], X Obradors[2], D C van der Laan[3,4], S A Dönges[3], J D Weiss[3,4], K Radcliff[3], P Cheetham[3], S Pamidi[5,6], D N Nguyen[7], L N Nguyen[7], R Bach[8], P Mansheim[8], R Prinz[9], D Willen[10], Alexander Alekseev[11], K McCullough[12], E Hodge[12], S Ishmael[13], M Luke[13], E Nilsson[14], J Rivenc[15], J-F Rouquette[14], L Ybanez[14], M Tassisto[14], F Berg[16], S Boukayoua[14], A Delarche[14], F Dunoyer[14], C Chaper[14], S Kharche[14], J M Baroille[14], C Räch[17], W Reiser[17], S Huwer[17], C Hanebeck[17], P Abrell[17], N Chikumoto[18], J-M Saugrain[19], A Allais[19], C H Ryu[20], J Y Lee[21], J W Cho[22], X Zong[23], B Wang[24], K Allweins[25], F Herzog[26], F Dioguardi[27], L Xiao[28], Q Qiu[28], T Arndt[1], S Palacios[1], M Wehr[1], M J Wolf[1], C-E Bruzek[29] and A Marian[30]

[1] Karlsruhe Institute of Technology, Karlsruhe, Germany
[2] ICMAB—CSIC, Campus University Autònoma de Barcelona, Barcelona, Spain
[3] Advanced Conductor Technologies LLC, Boulder, CO 80301, United States of America
[4] University of Colorado, Boulder, CO 80309, United States of America
[5] Center for Advanced Power Systems, Florida State University, Tallahassee, FL 32310, United States of America
[6] FAMU-FSU College of Engineering, Tallahassee, FL 32310, United States of America
[7] Los Alamos National Laboratory, Los Alamos, NM 87544, United States of America
[8] South Westphalia University of Applied Science, Soest, Germany
[9] Stadtwerke München, Munich, Germany
[10] NKT, Brøndby, Denmark
[11] Linde AG, Munich, Germany
[12] Supernode, Dublin, Ireland
[13] Veir Inc., Woburn, MA, United States of America
[14] Airbus UpNext SAS, Toulouse, France
[15] Airbus SAS, Blagnac, France
[16] Airbus Defense and Space, Ottobrunn, Germany
[17] Vision Electric Super Conductors GmbH, Kaiserslautern, Germany
[18] The University of Osaka, Osaka, Japan
[19] Nexans, Paris, France
[20] LS Cable & System Ltd, Anyang, Republic of Korea
[21] KEPCO KEPRI (Korea Electric Power Research Institute), Daejeon, Republic of Korea
[22] KERI (Korea Electrotechnology Research Institute), Changwon, Republic of Korea
[23] Shanghai International Superconductor Technology Co., Ltd (SISC), Shanghai, People's Republic of China
[24] School of Electrical Engineering, Beijing Jiaotong University (BJTU), Beijing, People's Republic of China
[25] Nexans Deutschland GmbH, Hanover, Germany
[26] Messer SE & Co. KGaA, Krefeld, Germany
[27] Stirling Cryogenics B.V., Eindhoven, The Netherlands
[28] Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, People's Republic of China
[29] ASG Superconductors, Genoa, Italy
[30] RIFS Potsdam, Potsdam, Germany
[*] Author to whom any correspondence should be addressed.

E-mail: mathias.noe@kit.edu

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Abstract

The energy transition requires a tremendous investment in electric grids, mainly due to electrification of heat and mobility sectors and due to the huge expansion of renewable energy. Superconductors offer an extremely high current density while having no resistance. In the past years, the cost-performance of high-temperature superconducting tapes decreased constantly, and the manufacturing capacity was expanded considerably.

In parallel, many AC and DC superconducting cables for various applications from low-voltage up to high-voltage levels have been developed, successfully tested and operated in field tests. The availability of the high-temperature superconducting tapes and the increasing need for network expansion result in an increased interest on the development of superconducting cables.

In this paper, the most important and most recent R&D activities on superconducting cables are summarized. The paper is structured in four main parts. Firstly, an introduction is given not only on the history of R&D but also on the high-temperature superconducting materials and conductors. The main part shows some selected R&D projects in more detail, while in the third part common issues relevant to all cables like cooling are discussed. The paper ends with contributions to hybrid superconducting cables, where electricity transport is combined with chemical energy carriers like liquid hydrogen.

It can be summarized that several projects demonstrated, that superconducting cables can fulfil all technical requirements for a long-term field operation and first permanent installations are realized. Attractive applications for superconducting cables include electric grids, high-current industry bus bars, data centers and aviation.

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1. Introduction

Mathias Noe

Karlsruhe Institute of Technology, Karlsruhe, Germany

The discovery of high-temperature superconductivity in 1986 by Bednorz and Müller [1] enabled the transport of large electric currents without resistance at the temperature level of liquid nitrogen at 77 K. This simplifies the cooling of the cable and increases the efficiency of superconducting cables considerably. With the high current density of superconductors and the vanishing resistance it is immediately clear that superconducting power cables can be made more compact and in general with lower losses. Figure 1 summarizes the main benefits of superconducting cables. Superconducting cables have major benefits in cable laying, for the environment and the operation of the cable. A more compact cable has less installation and laying effort and therefore an easier approval seems possible. Due to the co-axial structure of superconducting cables the electro-magnetic field outside the cable is zero and there is no ground heating of the environment. The current in conventional underground cables is usually not higher than around 1 kA without a cooling of the cable. With the high current of superconducting cables, the distribution and transmission capacity can be increased beyond values that are presently possible with conventional cables. In addition, superconducting cables offer several advantages for the operation of the cable. As an example, the Ferranti effect and the voltage drop along the cable is lower for alternating current (AC) cables.

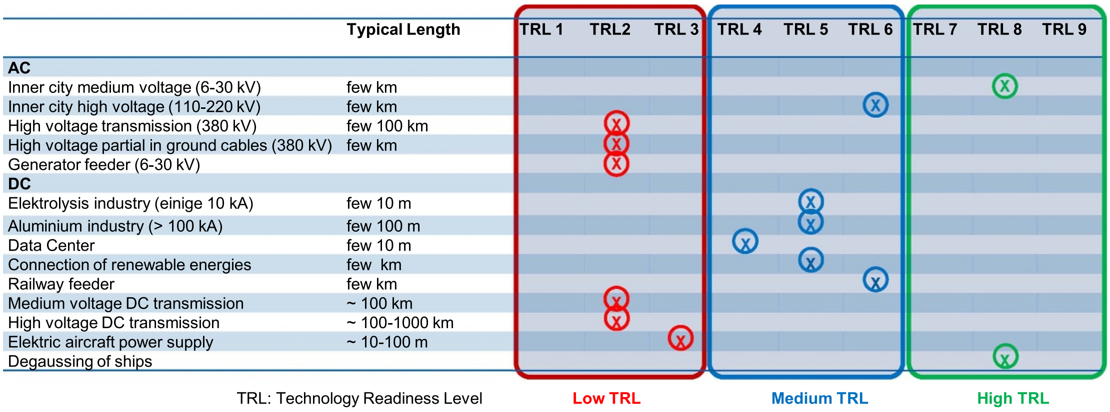
Despite the benefits of superconducting cables face challenges in comparison to conventional cables. The first and most obvious is an active cooling system that adds to the cost and decides about the reliability. In addition, the design depends on the cable length as temperature and pressure vary along the cable length and the maximum length without intermediate cooling stations is limited. Mainly, due to the cost of the cooling and the cryostat, a superconducting cable is still more expensive than a conventional cable with a similar power rating. The active cooling of superconducting cables requires auxiliary power so that there is a limited black-start capability of superconducting cables.

More than 35 years after the discovery of high-temperature superconductivity and more than 20 years after the first field-test installation of a HTS cable [2], superconducting cables and lines were developed successfully up to high voltage levels and several long-term field tests demonstrated a reliable operation. Nevertheless, superconducting cables and lines have not yet penetrated the commercial cable market and still some prejudices exist mainly about the cost and the reliability of superconducting cables. What is then the reason for a topical review on superconducting cables? Firstly, in the past decade, the manufacturing capabilities and the performance of 2nd generation superconducting material improved considerably. Whereas the first HTS cables were made with the so-called 1st generation Bi2223 tapes, nowadays nearly all cables use 2nd generation superconducting tapes based on rare-earth HTSs. Several companies worldwide have the capability to produce more than 100 km of tapes in a reasonable time-frame and with continuous quality [3]. At present, most HTS material manufacturers further invest to expand their pilot production lines into full industrial manufacturing lines. As a consequence, a further cost decrease can be expected. Secondly, the need for network extension increased considerably due to the energy transition towards zero emission energy systems. As an example, the latest network development plan in Germany states a need of more than 21 000 km by 2037 of additional 380 kV lines [4]. Due to an increasing number of electric vehicles and heat pumps a substantial network extension is needed at all voltage levels from low- to high voltages. Finally, the need to reduce carbon dioxide (CO_2) emissions increases the need for new technologies and makes savings more attractive. One example is the hybrid electric aircraft where compact and low weight superconducting cables are developed.

As figure 2 shows, there are many different applications where superconducting cables and lines were developed in the past. The technology readiness level is very different among the applications. Whereas medium voltage cables for urban areas with a length of a km have been field tested for long times in several locations [5], high voltage long distance cables are still in the technology concept status. AC superconducting cables were tested in grid for voltages up to 154 kV [6] so far. For direct current (DC), several superconducting cables and busbars were tested in various applications. The applications comprise large science applications like e.g. the large hadron collider (LHC), industry, data centers and railway feeders. At present, the length of superconducting cables was limited to not more than appr. 1 km but longer lengths are envisaged [7]. One company in the US announced the application of several superconducting DC cables for the degaussing of military ships but due to the military application no information on the cable is published.

- **Cable laying**
  - Smaller space and route requirements
  - Less efford in laying cables
  - Use of right of way for retrofit
  - Easier approval
- **Environment and marketing**
  - No electromagnetic fields outside the cable
  - No ground and soil heating
  - High energy and resource efficiency
- **Operation**
  - Higher distribution and transmission current
  - Lower voltage level (substitution of high voltage)
  - Lower impedance and lower voltage drop
  - Lower voltage rise at no load (AC cables)
  - Operation with natural loading possible (AC cables)

Figure 1. Advantages of superconducting cables and power lines.



	Typical Length	TRL 1	TRL2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
AC										
Inner city medium voltage (6-30 kV)	few km								x	
Inner city high voltage (110-220 kV)	few km						x			
High voltage transmission (380 kV)	few 100 km		x							
High voltage partial in ground cables (380 kV)	few km		x							
Generator feeder (6-30 kV)			x							
DC										
Elektrolysis industry (einige 10 kA)	few 10 m					x				
Aluminium industry (> 100 kA)	few 100 m					x				
Data Center	few 10 m				x					
Connection of renewable energies	few km					x				
Railway feeder	few km						x			
Medium voltage DC transmission	~ 100 km		x							
High voltage DC transmission	~ 100-1000 km		x							
Elektric aircraft power supply	~ 10-100 m			x						
Degaussing of ships									x	

Figure 2. Technology readiness level (TRL) of several superconducting AC and DC cables and lines. [8] John Wiley & Sons. © 2021 The Authors. Physik in unserer Zeit published by Wiley-VCH GmbH.

This contribution is structured in four main sections with 19 different contributions. A proper description of superconducting cables cannot be made without an overview on the present research and development of superconducting materials and the lessons learned from the many successful projects in the past. Presently, there are substantial activities to further develop superconducting cables for AC and high-current DC applications, and they are summarized in the second part. Recently, two start-up companies were founded, and their actual research and development status is also included. The third part of this paper covers the experience with a reliable operation and the cooling aspects. These contributions focus on the experience from field test applications and on future developments in this area. Hydrogen as an energy carrier is getting more and more attractive and due to the high energy density liquid hydrogen is expected to be widely used at least in some applications. This would favor the combination with superconductors very much because of its temperature of 20 K at pool boiling conditions. The last part of this contribution summarizes present research and development activities for hybrid energy lines with chemical and electricity transport in one line.

2. Status of HTS material R&D for superconducting cable

Teresa Puig and Xavier Obradors

ICMAB—CSIC, Campus University Autònoma de Barcelona, 08193 Bellaterra, Catalonia, Spain

Status

First generation superconducting tapes based on the $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi2223) phase has been on the basis of the first HTS cables developed during about 13 years (2000–2013). This HTS material has a high critical temperature T_c value ($T_c \sim 110$ K), it can be doped with several elements (Pb for instance) to tune the processing conditions and the superconducting properties and it is very well adapted to the powder-in-tube production methodology to achieve flat tapes using Ag tubes and thermomechanical processing. Thorough studies of the complex phase diagram have facilitated to create an industrial production methodology of long length monofilamentary and multifilamentary tapes [9]. The thermomechanical properties of this material were extremely adequate to induce a uniaxial texture based on crystallites having a platelet morphology after being generated during a liquid assisted high temperature process performed under a controlled temperature and PO_2 atmosphere. The strong uniaxial texture and the platelet morphology allowed to model the current percolation in monofilamentary tapes based on two different models, the so-called Railway-Switch and the Brick-Wall models. In the first case the limiting role of grain boundaries is emphasized while in the second model the currents along the *c*-axis appear as the limiting factor. The best adequacy of these models seems to depend on temperature, magnetic field and texture quality. In any case, rather high critical current densities at self-field and 77 K are observed (critical current density $J_c > 30$ kAcm^{-2}) [9]. The magnetic field dependence of the critical current density $J_c(B)$ at such high temperatures, however, was rather strong because the high electronic anisotropy of this HTS phase leads to a low Irreversibility Line and so a strong dependence $J_c(B)$. For that reason, the Bi2223 tapes have been mainly considered suitable for low magnetic field applications such as cables where ac losses could also strongly diminish using insulating oxide barriers such as $BaZrO_3$ to reduce coupling among filaments. Many prototype high power ac cable systems were demonstrated during 13 years. Industrial production of Bi2223 tapes has been continued during many years and also other applications, such as magnets working at low temperatures or current leads, have also been developed [10]. In more recent years, however, the industrial interest of these first generation BSCCO tapes in power systems has strongly declined owing to the more advanced performance and lower cost of second generation $REBa_2Cu_3O_7$ (RE = rare earth or yttrium, REBCO) coated conductors (CCs) which are the main choice at present for all cable applications.

The strong development during the last 20 years of CCs based on REBCO HTS, has allowed that these materials have emerged as the preferred choice for many electrical power and high magnetic field applications. Essentially a CC is a flexible multilayer architecture which consists of a metallic substrate, several buffer layers, the REBCO HTS layer and several protective layers (figure 3), where the main difficulty has been to achieve epitaxial growth to avoid the deleterious effect of grain boundaries [3, 11].

Several CC architectures combining different metallic substrates, buffer layers and REBCO phases have been investigated (figure 3) reaching outstanding superconducting performance and a few of them have become industrial products with lengths in the range of km suitable for power applications, particularly in cables [3, 12].

The cable application demands of CCs are quite diverse, i.e. electrical energy transport in ac and dc modalities, cryo-electrified transportation (airplanes for instance), electrical connections in industrial plants and big data centers [13] and even as energy storage systems in microgrids [14]. A common feature of all of them, however, is that cables work under self-field conditions, i.e. it is not required to precisely tailor the nanostructure to enhance vortex pinning as it has been done for high magnetic field applications.

The CC performance requirements for all these applications may slightly differ and the cooling route may also be different (liquid N_2, liquid H_2, He gas or cryocoolers) [15]. For that reason, even if the performance is similar, the preferred architecture and how the different manufacturing methodologies adapt to the demands, may differ.

There are essentially three different architectures investigated up to now: (i) thermomechanical textured metallic substrates rolling assisted biaxial texture with epitaxial oxide buffer layers; (ii) polycrystalline hastelloy or stainless steel substrates with textured buffer layers deposited through ion beam assisted deposition (IBAD); and (iii) polycrystalline substrates with textured buffer layers deposited through an inclined substrate deposition (ISD) approach. The preferred commercial approaches at present

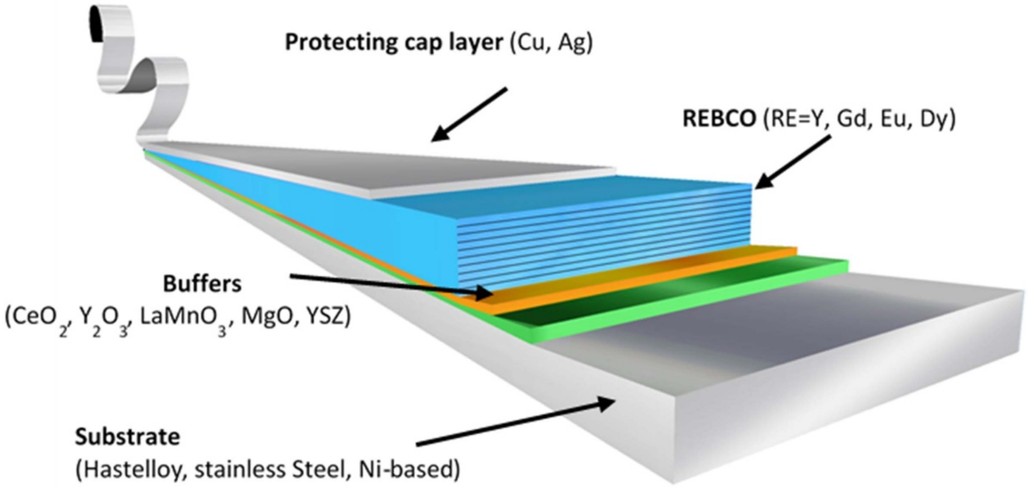


Figure 3. General schema of the coated conductor architecture. REBCO = REBa$_2$Cu$_3$O$_7$, where RE is a rare earth or yttrium.

are the IBAD and ISD, mainly due to their enhanced mechanical properties associated to the metallic substrates.

The deposition methodologies of REBCO layers with strong commercial attractiveness are also diverse, some of them grow from vapors, others from intermediate solid phases and other through intermediate liquid phases [3, 12]. The main players at present are: pulsed laser deposition (PLD) and high rate, metalorganic chemical vapor deposition, reactive co-evaporation and direct growth (RCE-DR), metal evaporation, chemical solution deposition (CSD) by trifluoracetate route, and through transient liquid assisted growth (CSD-TLAG) [3, 16]. In all cases the REBCO layers are coated with protective layers of Ag and Cu or even other metals or ceramics. This is of high relevance when the electro-thermal protection of CCs is considered for high power applications (cables, fault current limiters and fault-tolerant cables) [12].

The best performances achieved in terms of critical current (I_c) at 77 K and 20 K, under self-field conditions which is the closest working conditions in most of the cables, are 500–1.000 A cm^{-1}-w and 2.500–9.000 A cm^{-1}-w, respectively, where the A/cm-w unit corresponds to the critical current displayed by a CC with a width of 1 cm [17–20]. However, other parameters need to be also scrutinized for each application, including the cost of the processing methodology, the mechanical properties, ac losses and the robustness against quench events, as discussed below [15].

Current and future challenges

Nowadays, CCs are a reality which have enabled to demonstrate cable applications, however the CC community is facing several challenges to make this technology pervasive as a commercial product in electrical power applications. We can summarize the current and future challenges in five different topics.

First, it is essential to expand the industrial **volume production** capabilities in all the commercial approaches. The present estimated worldwide production is 3.000–5.000 km yr^{-1} while it is estimated that this value will be twice in 2025 and it will have multiplied by ~8 in 2028 [21]. This increase will be a consequence of further improving the manufacturing layouts and increasing the throughput and yield, through modified growth units and also by increasing the length of the achieved conductors to reduce the number of required joints in practical devices such as cables. All this will bring strong availability of CCs to deploy the many key different demonstrations. The second is to decrease their **cost**. The present typical cost is in the range 80–100 € kA^{-1} m when J_c is measured at 77 K and self-field and it is estimated that this value could be reduced by ~50% in the next 4–5 years [22]. Increasing the CC volume production and yield will contribute to reduce the unitary cost due to the scaling effects. The growing demand of CC is certainly supporting this trend and so the manufacturing units are being expanded worldwide for all the growth methodologies. However, this will probably not be enough and other strategies will need to be followed (see next section).

A third common challenge of all the CC manufacturing routes is to enhance the **engineering critical current density** J_e. This value is determined by the thickness of the non-superconducting layers of the

CC (mainly the metallic substrate and protective layers) and by the critical current of the REBCO layer $I_c = J_c\ t$, where t is the thickness of the REBCO layer and J_c the critical current density. The present typical J_e values at the commercial level are in the range 30–60 kA cm^{-2} at 77 K and 150–300 kA cm^{-2} at 20 K, while at the laboratory scale these values can be more than 100% higher. The efforts to reduce the thickness of the metallic substrate is not expected to reduce the present demonstrated t values in the range of ~30 μm [23]. Additionally, most of the growth techniques have demonstrated, at the laboratory scale, high quality epitaxy and high J_c values for REBCO thickness in the range of 2–4 μm [23, 24]. However, this high thickness is still a challenge for the commercial products.

The fourth challenge is actually a very stringent demand when integrating CCs in cables, which is the need to support the **electro–thermal–mechanical stresses** specially during a possible quench (which rises the CC temperature beyond T_c) and fabrication. Cables should be fully fault-tolerant after its installation (specially in underwater or airplane systems) so it is a stringent challenge to disclose how to assure this very demanding safety and reliability issues. These requirements underline two distinctive challenges for the future development of existing CCs. One is to maximize the strain and stress limits to keep performance, as well as reaching safe limits against delamination of CCs. The other is to increase the normal zone propagation velocity (NZPV), which is known to be excessively low in CCs, which makes them excessively unprotected against hot spots [25]. It is also worth to mention that REBCO CCs have a high stress tolerance, >500 MPa, since they are grown usually on Hastelloy metallic substrates [26]. Finally, the fifth challenge, which probably is the most advanced, is that related to **ac-losses**. Integration of CCs in several types of cable devices requires to assemble them in robust conductors combining a large number of single conductors with different shapes, displaying either low ac losses (using striated conductors) or standard CCs when being used in dc operation [27]. It is particularly worth to mention the use of round cables based on filamentizated CCs which display strongly reduced ac losses [28–30].

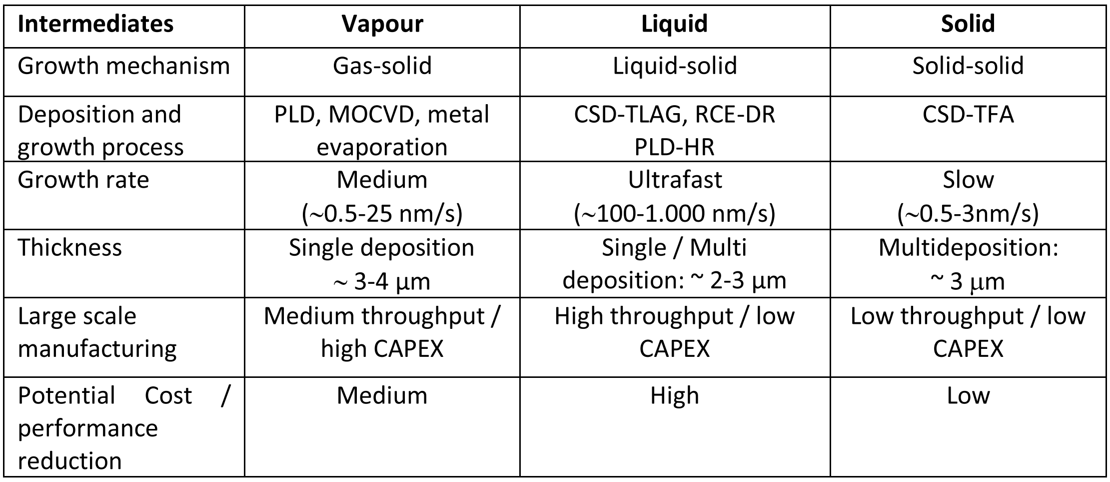
Advances in science and technology to meet challenges

The three first challenges defined in the previous paragraph are actually combined in a single figure of merit to characterize the competitiveness of any type of CC manufacturing option. The figure of merit can be defined as a ratio cost/performance, i.e. the total cost share per year/performance [12, 31]:

$$\frac{\text{Cost}}{\text{Perfomance}}\left(\frac{€}{\text{kA m}}\right) = \frac{\text{total cost per year}}{G \cdot L \cdot W \cdot J_c}$$

where G is the growth rate of the REBCO layers, L the length produced per year and W the width of the CCs. The J_c values of the REBCO layers are defined under the working conditions for any specific device, typically at 77 K and self-field for cables. The total annual cost is the ratio between the annual expenditures (€), including CAPEX depreciation, and the CC production throughput (REBCO volume production rate, i.e. m^3 s^{-1}). Several scientific and technological advances are devised to reduce this figure of merit. The manufacturing volume may be enhanced through an increase of *Length* or *Width* or even by implementation of double sided CCs where REBCO is grown in both sides of the metallic substrate [32]. Several efforts are being also deployed to develop IBAD metallic templates with widths in the range of +100 mm which in certain processing methodologies would allow to increase the manufacturing volume without any significant increase of the CAPEX. The annual production lengths would be also enhanced if a single reel-to-reel run could go well beyond the present upper limit of ~1 km by using advanced *in-situ* characterization tools including feedback in the processing unit [24]. Efforts are also being made to develop superconducting joints between CC pieces which would in addition minimize the losses in the cables. The present best resistive joints achieved for CCs are in the range of ~15 nΩ (interface resistance, R_i < 80 nΩ cm^2) at 77 K and self-field [33, 34], although intensive research effort is being carried out also to develop superconducting joints among REBCO CCs which leads to R_i values below ~3 10^{-12} Ω [35].

The parameter of the figure of merit which is being increased very significantly is the REBCO growth rate G. The main source of significant progress in this parameter is the liquid mediated growth routes where G values increased by a factor 10–100 are being obtained in the TLAG [36], RCE-DR and PLD-LHR [12]. If these approaches can facilitate the enhancement of the film thickness t, higher I_c values would also be achieved while advances in the increase of J_c at self-field can also be expected by tuning the carrier concentration [12, 37]. Advances in defining suitable combinations of the many processing parameters to optimize growth conditions and performance should deeply benefit of the use of artificial



Intermediates	Vapour	Liquid	Solid
Growth mechanism	Gas-solid	Liquid-solid	Solid-solid
Deposition and growth process	PLD, MOCVD, metal evaporation	CSD-TLAG, RCE-DR PLD-HR	CSD-TFA
Growth rate	Medium (~0.5-25 nm/s)	Ultrafast (~100-1.000 nm/s)	Slow (~0.5-3nm/s)
Thickness	Single deposition ~ 3-4 µm	Single / Multi deposition: ~ 2-3 µm	Multideposition: ~ 3 µm
Large scale manufacturing	Medium throughput / high CAPEX	High throughput / low CAPEX	Low throughput / low CAPEX
Potential Cost / performance reduction	Medium	High	Low

Figure 4. Summary of growth modes and performance characteristics of the different CC manufacturing techniques at industrial scale and prospective for their future evolution in terms of cost reduction and volume manufacturing. CAPEX = capital expenses.

intelligence and machine learning tools from data analyses using high throughput growth and superconducting characterization [38]. Figure 4 summarizes the present and prospective performances of the different growth modes of CCs.

Finally, CCs need to be further optimized to handle the strong mechanical, thermal and electrical stresses, particularly during the assembled conductor manufacturing step and quench events [15, 26, 27]. The mechanical robustness is mainly determined by the mechanical properties of the metallic substrate, so any mean to strengthen it would be beneficial. Additionally, defining optimized multilayers and growth conditions to maximize the interlayer adherence is also very relevant to minimize uncontrolled film delamination problems. One particular parameter defining the optimal thermal-electrical properties of CCs is the thicknesses of the protective coatings (particularly Cu), which should be determined for each cable application. But this has to be done in connection with the efforts to enhance the NZPV to enhance the thermal stability of cables based on CCs. Several ideas are being investigated which have already increased the NZPV by a factor ∼10 [25]. For instance, the concept of current flow diverter (CFD) has been successful in this goal [25]. This is based on modifying the interfacial resistance of the REBCO layers with the electrical protective layers (usually Ag), for instance using other alloys, such as Ag_2S or $AgIn_2$, or modifying the interfacial geometry [39].

Concluding remarks

The development of CCs has been an extraordinary achievement of materials science. Never before had it been demonstrated that it was possible to fabricate epitaxial structures in the km length range, neither for a structure of such a complexity as that of $REBa_2Cu_3O_7$. Several processing methodologies have been successful in demonstrating that CCs can be very competitive commercial products that show high superconducting performance and are a reliable and reproducible material. Therefore, many power applications are being developed today because CCs are a mature product that allows the construction of robust electrical engineering devices, such as power cables, one of the HTS system with the highest technology readiness level at present.

In this article we have summarized the main progress already made and also discussed the challenges ahead and how to address them. In particular, we have discussed how the cost of CCs is expected to be reduced and the annual manufacturing volume increased. We have emphasized that the cost/performance ratio figure of merit can be reduced by further developing the ultrafast liquid assisted growth processes, as well as by increasing the volume of simultaneous growth (larger widths, double-sided). Finally, we have emphasized the importance of further progress in improving the mechanical properties of CCs, as well as their thermal stability against quench events in order to gain resilience in working conditions. In conclusion, although CCs are already reliable engineered products, further developments are expected to contribute to their penetration as key elements in electrical power cables in the coming years.

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3. High current and high power density CORC® power cables and wires for dc and ac applications

D C van der Laan[1,2], *S A Dönges*[1], *J D Weiss*[1,2], *K Radcliff*[1], *P Cheetham*[3], *S Pamidi*[3,4], *D N Nguyen*[5] *and L N Nguyen*[5]

[1] Advanced Conductor Technologies LLC, Boulder, CO 80301, United States of America
[2] University of Colorado, Boulder, CO 80309, United States of America
[3] Center for Advanced Power Systems, Florida State University, Tallahassee, FL 32310, United States of America
[4] FAMU-FSU College of Engineering, Tallahassee, FL 32310, United States of America
[5] Los Alamos National Laboratory, Los Alamos, NM 87544, United States of America

Status

A growing number of applications, such as, but not limited to future electric ships and electric passenger aircraft, need generation and distribution of electric power in the range of several tens of megawatts. Space constraints require flexible cables that allow bending to radii of less than 0.5 meters and, in many cases, limit their operating voltage to below 3 kV. Hence, there is a need for power dense ac and dc cables operating at currents ranging from 1 to 10 kA. Restrictions on mass and heat loads in many transportation applications make HTSs such as RE-$Ba_2Cu_3O_{7-\delta}$ (REBCO) CCs the only viable candidate. Future electric aircraft could use liquid hydrogen as fuel that would act as a cold sink, removing the cost and weight penalties of the cryogenic cooling infrastructure necessary for HTS equipment. Operation at 20–50 K becomes possible, likely using pressurized helium gas as the secondary loop coolant to avoid the risks associated with cooling directly with liquid hydrogen. The much lower cable operating temperature, compared to the limited 65–80 K range accessible with liquid nitrogen, allows much higher operating currents or a reduced number of REBCO tapes, resulting in a significant cost reduction.

Several HTS cable designs have been developed and demonstrated for high-current power transmission [15]. Conductor on Round Core (CORC®) cables, developed by Advanced Conductor Technologies (ACT) [28], is a viable solution for many high-power applications that come with space and weight constraints. Operation of single-pole (figure 5) and coaxial 2-pole CORC® cables with a solid metal core have been demonstrated with liquid nitrogen [40, 41] and gaseous helium cooling [42, 43]. Electrical insulation compatible with helium gas cooling, consisting of several layers of polyimide tape with a total thickness of 1 mm, has also been developed [44]. Figure 5 lists the operating current (I_{opp}) at about 70% of the critical current (I_{c}) of the various CORC® cable layouts when operated at 68–77 K in liquid nitrogen and at 30–50 K with flowing pressurized helium gas. Also listed is their rated power when operated at a voltage of 3 kV.

Current and future challenges

High power-dense applications need operating currents as high 6 kA in liquid nitrogen, which requires a high number (up to 48) of REBCO tapes cabled in a compact, flexible cable configuration. Terminating such cables in a low-resistance terminal while ensuring uniform current distribution among the tapes is challenging. In addition, some applications require a higher level of bending flexibility than the 0.1–0.25 m radius achievable with high-current CORC® cables that contain a dielectric. Therefore, thinner, more flexible CORC® wires that can be bent to radii less than 0.1 m need to be developed with a dielectric compatible with liquid or gaseous cryogens or even conductive cooling.

CORC® cables experience relatively low losses, in the order of 1 W m^{-1} or less, when operating at ac currents with frequencies of 50–60 Hz [45]. Cable dielectrics that are not impregnated with liquid nitrogen, as in HTS cable applications for electric utilities, form a thermal barrier between the tapes and the external coolant. This thermal barrier of the dielectric could result in substantial heating of the REBCO tapes when operated at ac currents of high frequency, such as in the 500 Hz ac bus between the motor control unit (MCU) and the motor in the electric aircraft powertrain of the Airbus Advanced Superconducting and Cryogenic Experimental power train Demonstrator (ASCEND) demonstrator [41]. Figure 6 shows the transport ac losses of a 24-tape CORC® cable with 1 mm thick polyimide insulation as a function of peak operating current at different frequencies up to 507 Hz. The cable I_{c} is estimated at about 3.11 kA at 77 K and about 3.88 kA at 75.5 K. Although the surface of the cable was cooled with liquid nitrogen at 75 K, the temperature measured by a Cernox temperature sensor, embedded between the REBCO tapes and the insulation, increased from 75 K to 75.5 K when operated at 507 Hz

	a. CORC® cable	b. CORC® wire	c. CORC® cable
Core	Solid	Solid	Hollow
Core diameter [mm]	5.4	2.55	6.35
Poles	1	1	1
Tapes per pole (width)	48 (4 mm)	30 (2 mm)	24 (4)
Dielectric thickness [mm]	0.2	0.2	0.2
Operating voltage [kV]	3	3	3
Overall thickness [mm]	8.1	4.0	7.8
I_{opp} @ 68 – 77 K [kA] *	3.5 – 7	1.5 – 3	2 – 4 (dc)
I_{opp} @ 30 – 50 K [kA] *	14 – 28	6 – 12	8 – 16 (dc)
Rated power @ 68 – 77 K [MW]	10 – 20	4.5 – 9	6 – 12 (dc)
Rated power @ 30 – 50 K [MW]	42 – 84	18 – 36	24 – 48 (dc)

* Depending on the HTS supplier and batch number

Figure 5. Overview of the high-current and high current density CORC® cable and wire solutions for power applications. The range includes single-pole CORC® power cables and highly flexible CORC® wires with solid core for dc applications, and CORC® cables with hollow core for high-frequency power applications. A list of the main specifications is provided below each conductor.

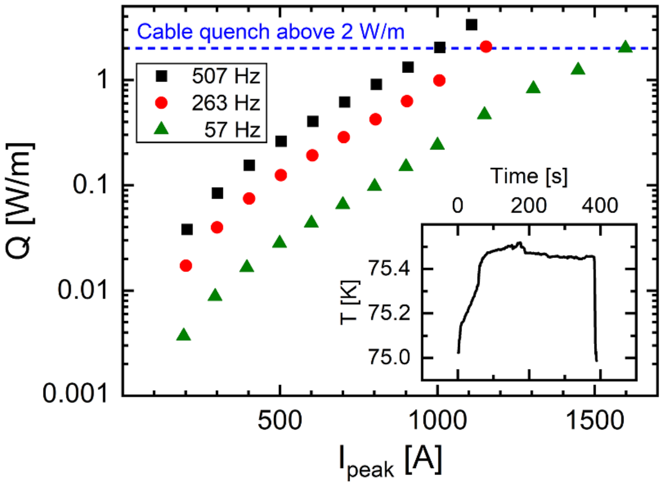

Figure 6. Ac loss of a 24-tape CORC® cable measured at 75 K in boiling liquid nitrogen as a function of peak current. The cable contained a 1 mm thick wrapped polyimide dielectric. Measurements were taken at frequencies of 57.3, 263, and 507 Hz. The dashed line indicates the loss of 2 W m^{-1} at which the cable would quench, independent of frequency. The inset shows the temperature as a function of time measured between the REBCO tapes and cable dielectric when operated at 507 Hz and a peak current of 998 A.

and a peak current of 998 A (Inset figure 6). The cable quenched as soon as the peak current reached 1110 A. Even at lower frequencies, the cable quenched when the ac loss exceeded 2 W m^{-1}, which seems to be the threshold at which cooling though the dielectric is no longer sufficient.

Advances in science and technology to meet challenges

As reported recently [44], ACT has developed lightweight 2-pole coaxial CORC® power cables with solid cores for electric aircraft. The 12 REBCO tapes per pole support an operating current of 5 kA at 30 K. The 1 mm thick wrapped polyimide dielectric is sufficient for an operating voltage of 10 kV, resulting in a 50 MW class cable. Such a high operating current is more difficult to achieve at the

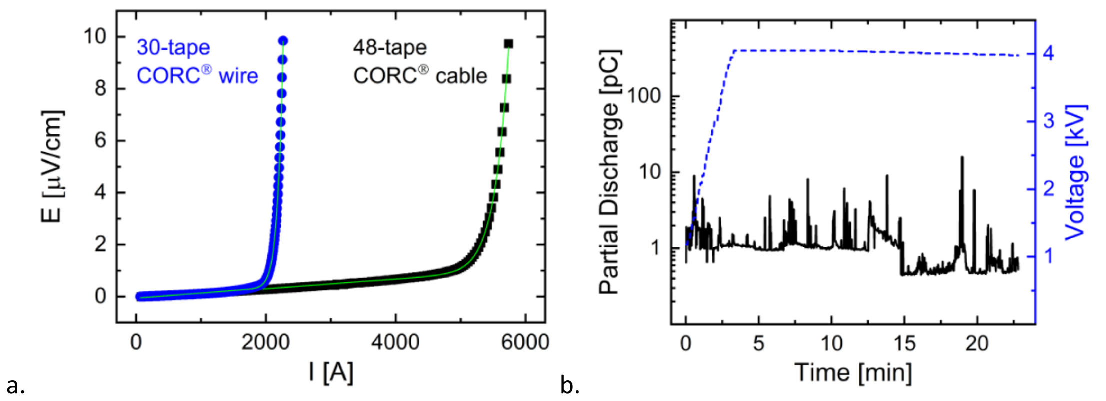

Figure 7. (a) Electric field as a function of current measured in boiling liquid nitrogen at 76 K of a 48-tape CORC® cable and a 30-tape CORC® wire containing a 0.2 mm thick polyimide dielectric. Green lines are fits to determine critical current and n-value (b) partial discharge as a function of applied voltage at 77 K in vacuum of a 3.2 mm thick copper conductor containing a 0.2 mm thick wrapped polyimide dielectric.

65–77 K temperature range accessible with liquid nitrogen cooling because a much higher number of REBCO tapes needed to be cabled (at least 48 tapes per pole). Figure 7(a) shows the electric field as a function of the current of a 7.7 mm thick single-pole CORC® power cable containing 48 REBCO tapes of 4 mm width in boiling liquid nitrogen at 76 K. The voltage was measured with contacts embedded between the cable and the copper terminations that were custom developed for CORC® cables [46]. The measurement resulted in an I_c of 5,285 A (n-value = 27) and contact resistance of the terminals of 30.3 nΩ. The high n-value and linear slope over the entire current range before the superconducting-to-normal transition are indications of an even current distribution among the tapes in the cable. The cable is expected to have an I_c above 10 kA at sub-cooled liquid nitrogen below 70 K. A 1 mm thick polyimide dielectric would thus support a power rating of 50 MW at liquid nitrogen temperatures. On the other hand, a 3 kV dielectric would support a 10–20 MW power rating in liquid nitrogen (table 1) without the design challenges associated with a 10 kV cable, such as longer creepage distances, cable stress cones, and corona rings.

Figure 7(a) shows the electric field as a function of current measured over the terminals of a 3.6 mm thick CORC® wire with 30 REBCO tapes of 2 mm width. This wire had an I_c of 2,080 A (n-value = 26) at 76 K, providing it with a current rating of 1.5 kA at 76 K, 3 kA at 68–70 K using sub-cooled liquid nitrogen, and about 12 kA at 30 K (table 1). The CORC® wire contained a 0.2 mm thick dielectric formed by winding four layers of 0.025 mm thick polyimide tape with 30% overlap onto its surface (figure 5(b)), resulting in a total conductor thickness of 4.0 mm. The partial discharge of a 3.2 mm thick copper conductor with the same dielectric, measured in vacuum at 77 K (figure 7(b)), remained below the partial discharge inception threshold of 10 pC apparent charge up to a voltage of 4 kV, confirming its voltage rating of 3 kV. The highly flexible CORC® power wire thus has a power rating of 9 MW at 68–70 K and 36 MW at 30 K.

In high-frequency ac applications, CORC® cables benefit from lower operating temperatures that increase I_c and reduce the ac losses for a given operating current and frequency. In addition, improved cooling would likely allow CORC® cables to operate safely when experiencing ac losses above 2 W m^{-1}. Figure 5 includes a CORC® power cable with a hollow core that facilitates internal cooling [47]. The 6.35 mm diameter copper core contains a 4.8 mm diameter opening that allows sufficient cryogen flow for cooling cables that are tens of meters long. The cable contains 24 REBCO tapes wound three tapes per layer with less than 0.2 mm spacing between them. CORC® cables with larger hollow cores have also been developed, allowing for low pressure drop and therefore, suitable for longer length applications. For example, a 24-tape CORC® cable with a 10 mm diameter hollow core and 8 mm diameter opening in which each of the 4 layers containing 6 tapes has recently been successfully manufactured. CORC® cables can be further optimized to contain a larger copper fraction by either apply REBCO tapes containing a thicker layer copper layer, or by winding additional copper tapes within, or between the REBCO layers.

Concluding remarks

CORC® power cables and wires with 4.5 to over 80 MW power ratings, depending on the operating temperature and conductor layout, have been developed. Operating them at a high current and a voltage of

3 kV comes with significant advantages over power cables that operate at higher voltages and lower currents. Although applying a 10 kV dielectric to the CORC® power cables and wires outlined in this paper is possible, the lower operating voltage of 3 kV makes the cable termination design and manufacturing less complex. Shorter creepage distance and lower electric stresses at the cable terminations eliminate the need for stress cones and corona rings for cables operating at 5 kV or higher. Implementing CORC® power cables and wires has become relatively straightforward, while the risk of partial discharge that may lead to flashover or breakdown is minimized. Low voltage CORC® power cables and wires rated at 4.5–80 MW are thus an attractive solution for many groundbreaking high-power applications.

Acknowledgments

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4. Lessons learned from history and past projects

Mathias Noe

Karlsruhe Institute of Technology, Karlsruhe, Germany

From the late 1960s several projects initiated from companies and research institutes started to develop power transmission cables with LTSs. Table 1 gives an overview on some of these projects.

The projects included terminations and cooling and demonstrated in most cases the technical feasibility of these cable installations. A first field test trial of a superconducting cable started in 1979 at Arnstein in Austria [48]. All other low-temperature superconducting cables were tested in dedicated test facilities either at research institutes or companies. The longest low-temperature superconducting cable was successfully developed and tested at Brookhaven National Laboratories [49].

It is assumed that these projects were initiated mainly because of the progress in cryogenic cooling and the energy increase that envisaged high power transmission networks with GW lines latest by the end of the century. Despite the technical progress made within the projects no further cable project was initiated by the mid of the 1980s. A main reason for this was at that time that a cost break even for low-temperature-superconducting cables can be expected at a rating of several GWs only and that the power increase slowed down by the mid of the 1970s. Latest with the discovery of high-temperature superconductivity in 1986 by Bednorz and Müller, the benefit with liquid nitrogen cooling at 77 K was quite obvious and no further R&D on low-temperature superconducting cables took place.

Then it took until 2000 since the first HTS cable was demonstrated in a field test trial in Carrollton, GA, US [50] with a 30 m, 12.5 kV, 1250 A lines using BSCCO tapes. This was the beginning of more than a decade of several HTS cable demonstrations. Table 2 summarizes the main projects and data of HTS AC cable field test trials.

Some important lessons learned were taken from the first field test trials of HTS cables in Detroit and Copenhagen, which took place nearly at the same time in 2001. Pirelli reported at the DOE peer review in 2002 that ‘after extensive testing of the three HTS cables it installed at the Frisbie substation it has determined that leaks in two of the cables are significant enough that they cannot be energized’ [51]. This problem was not fixed and as a consequence the cable was not energized and soon after Pirelli stopped to further develop superconducting cables. As a result of the first field test of a HTS cable in Europe in Copenhagen it was reported in [52] that ‘the cooling system did not have the desired reliability and maintainability for continuous operation in a utility environment’. These two items of reliable cooling and thermal insulation of the cable are obviously the two main factors for a reliable operation of a superconducting cable.

Since then, several successful field test installations of HTS cable systems took place. Most of these projects were R&D projects with a limited test period for the cable. So far, superconducting AC cables with voltages up to 154 kV, currents of up to 3 kA and lengths of 1.2 km were tested in field test trials and it was demonstrated very clearly that superconducting cables fulfill all operational requirements of the utilities. The first HTS cable using YBCO tapes was the so-called LIPA cable installed in 2008 [53]. Nowadays, nearly all superconducting cables rely on YBCO tapes mainly due to the wider availability and the improved cost performance ratio.

The cable with the longest continuous field test operation so far is the 10 kV, 40 kA, 1 km AmpaCity cable, installed in 2013 in the inner city of Essen, Germany [54]. The cable was planned for a test installation of not more than 2 years, but due to the exceptional performance of the cable this time was extended to 7 years. The three main lessons learned from this project are, firstly that small leaks at the terminals can be fixed during the commissioning phase, secondly that the capacitive imbalance of a three-phase concentric cable needs a compensation and thirdly that a superconducting cable needs no disconnection during an open–close-cycle of a fault. During operation this cable was considered like any other cable in the network. It has to be mentioned that since the Detroit cable, no degradation of a superconducting cable was reported. As a result, it can be expected that superconducting cables can reach a long lifetime similar to conventional cables. In the meantime, an international standard for testing superconducting AC cables was developed [55].

Table 3 gives an overview on the development of HTS DC cables. Two main R&D directions can be distinguished. One is the development of HVDC cables and the other is low-voltage, high-current applications for e.g. industry, data centers or railway. Within a European project a type test of a 320 kV

Table 1. Overview on selected projects to develop low-temperature superconducting cables.

Place	Country/year	Data	Length	Superconductor
Arnstein	Austria/1979	66 kV, 1000 A	50 m	Nb
Brookhaven	US/1982	138 kV, 1000 MVA	115 m	Nb_3Sn
Siemens	Germany/1977	110 kV, 10 kA	35 m	NbAl
Japan	Japan/1991	20 kV, 2 kA	15 m	Nb
Moscow	Russia/1978	110 kV, 12 kA	50 m	Nb_3Sn

Table 2. Overview on field tests of high-temperature superconducting AC cables.

Place/Company	Country/year	Data	Length	Superconductor
Carollton/Southwire	US, 2000	12.5 kV, 1250 A	30 m	BSCCO
Detroit/Pirelli	US, 2001	24 kV, 100 MVA	120 m	BSCCO
Copenhagen/Nkt	Denmark 2001	30 kV, 2 kA	30 m	BSCCO
Yokosuka/Furukawa	Japan/2004	77 kV, 1 kA	500 m	BSCCO
Gochang/Sumitomo	Korea/2006	22.9 kV, 1.25 kA	100 m	BSCCO
Columbus/Ultera	US/2006	13.2 kV, 3 kA	200 m	BSCCO
Albany/Sumitomo	US/2006	34.5 kV, 800 A	350 m	BSCCO
Gochang/LS Cable	Korea/2007	22.9 kV, 1.26 kA	100 m	BSCCO
Long Island/Nexans	US/2008	138 kV, 2.4 kA	600 m	BSCCO, YBCO
Icheon/LS Cable	Korea/2009	22.9 kV, 1.3 kA	500 m	BSCCO
Moscow/VNIIKP	Russia/2009	20 kV 1.5 kA	200 m	BSCCO
Icheon/LS Cable	Korea/2011	22.9 kV, 3 kA	100 m	BSCCO
Yokohama/Sumitomo	Japan/2013	66 kV, 1.8 kA	240 m	BSCCO
Essen/Nexans	Germany/2013	10 kV, 2.4 kA	1000 m	BSCCO
Jeju/LS Cable	Korea/2016	154 kV, 600 MVA	1000 m	YBCO
Shingal/LS Cable	Korea/2019	22.9 kV, 50 MVA	1000 m	YBCO
Totsuka/Showa	Japan/2020	11 kV, 3 kA	200 m	YBCO
Chicago/Nexans	US/2021	12 kV, 3 kA	200 m	YBCO
Shanghai/SECRI	China/2021	35 kV, 2.2 kA	1200 m	YBCO
Shenzhen/CSG	China/2021	10 kV, 43 MVA	400 m	YBCO
Munich/nkt cables	Germany/2024	110 kV, 500 MVA	120 m	YBCO

Table 3. Overview on selected projects to develop high-temperature superconducting DC cables and busbars.

Place	Country/year	Application	Data	Length	Superconductor
Chubu	Japan/2010	Test	10 kV, 2 kA	200 m	BSCCO
Gongyi	China/2012	Aluminum industry	1.3 kV, 10 kA	360 m	BSCCO
Kunitachi	Japan/2012	Test	1.5 kV, 6 kA	30 m	BSCCO
Jeju Island	Korea/2015	HVDC	80 kV, 3.25 kA	500 m	YBCO
Ishikari	Japan/2015	Data center	20 kV, 5 kA	500 m	BSCCO
Ludwigshafen	Germany/2017	Electrolysis	1 kV, 20 kA	25 m	YBCO
Bestpaths	France/2019	HVDC	320 kV, 10 kA	30 m	MgB_2
Hino	Japan/2019	Railway	1.5 kV, 2.2 kA	408 m	—
St. Petersburg	Russia/2021	MVDC	20 kV, 2.5 kA	2400 m	BSCCO
Myazaki	Japan/2022	Railway	1.5 kV, —	1500 m	—
Shanghai	China/2023	HVDC	35 kV, 2.2 kA	1200 m	YBCO
Paris	France/2024	Railway	1.5 kV, 3 kA	120 m	YBCO

superconducting HVDC cable took place [56] and technology development for an industry busbar with 200 kA is also ongoing [57]. The longest superconducting cable that was tested so far is a 20 kV, 2.5 kA, 2.4 km DC cable for connecting two substations in St. Petersburg, Russia [58]. Although less field test trials took place with superconducting DC cables in comparison to AC cables, the lower heat input of DC cables due to zero AC loss, would favor DC cables and enables longer length without a re-cooling and lower cooling power.

Concluding remarks

Several prototype installations of HTS AC and DC cables have clearly demonstrated that superconducting cables can be operated reliably and that they fulfill all operational requirements of the utilities. So far, superconducting cables with voltages of up to 320 kV, currents up to 20 kA and lengths up to 2.4 km have been developed. The challenge today is mainly to identify applications where the higher cost of the superconducting cable is compensated by additional system benefits. For example, this can be the case in urban areas with limited right of way and in several DC applications. The tendency of the most present R&D activities is to reduce the system cost, to install more long-term or even permanent cable systems and to demonstrate a longer cable length. A major difference in comparison to conventional cables is simply that a superconducting cable is not completely passive due to the cooling but a reliable cooling system with a high degree of redundancy has been demonstrated several times.

5. SuperLink high-power cable for urban areas

Robert Bach[1], *Patrick Mansheim*[1], *Dag Willen*[2]
and Alexander Alekseev[3]

[1] South Westphalia University of Applied Science Robert Prinz, Stadtwerke München
[2] NKT, Denmark
[3] Linde AG, Germany

Status

The discovery of 2G-HTS and a critical temperature T_c above the boiling point of liquid nitrogen LN2, combined with less complex and more cost-effective cooling, led to the launch of many HTS AC cable projects. In Europe, the USA and Asia, large pilot projects have been realized and proven the performance and reliability of HTS cables. The AC cables in the projects showed excellent ratio of diameter versus power transport capacity. The main constructions of HTS-Power cables are with cold dielectric, which means that HTS-conductor is isolated with a wrapped dielectric impregnated with liquid nitrogen and often with an HTS-shielding. The corresponding auxiliary accessories consist of cryogenic coolers, tanks and pumps [59]. In projects such as the AmpaCity project (Germany), the LIPA project (USA), and the AEP project (USA), full grid integration and grid operation have been impressively demonstrated [60–62]. On the way to technological integration of a commercial design, economic aspects are increasingly taking center stage [63]. The realized projects all have a limited cable length by around 1 km, as the cooling system in particular poses a challenge for long cable lengths. In the project ‘Superlink’, the concept for a 15 km long, superconducting, 500 MVA 110 kV-cable connection across Munich, including all necessary components, is developed, type-tested and prequalification-tested. All components are to be installed in a demonstration setup in the DSO power grid in a substation in Munich in the project’s construction phase and operated for approx. 6 months under operating voltage with different load cycles. Besides the main project, the feasibility of the HTS solution for this type of electrical transport requirement (500 MVA and 15 km, urban area) is evaluated. Following the results of the project and the power grid test, the grid operator will decide on the tender and realization of the 15 km long main connection line to the south of the city.

Current and future challenges

The cooling system is a key component for availability and economic efficiency. The electrical losses in the used cable construction are greatly reduced. Compared to conventional (XLPE-)cable solutions, in the past the thermal losses and energy requirements for the pump systems were the reason, why there were no loss benefits for many demonstration projects [59]. This is why the losses are of specific interest for the Munich project to reach an economic state. The Munich cable structure uses a three-conductor cable with all three cores in one cryostat. The rated voltage is 110 kV and the rated current is 2.6 kA rms for 500 MVA of transported power. The cable is subject to a safety-oriented design and is constructed to tolerate short-circuit currents of up to 40 kA for 1 s in order not to require a fast circuit breaker used in other projects [60, 62]. The cable is shown in figure 8. The structural requirements and the aim of achieving the most compact design possible result in high requirements for the extensive cooling system, posing a challenge for long cable length [64, 65]:

- A separate liquid nitrogen cryostat return line for the closed loop circulation is used; thus the maximum cable length can be extended without the need for additional intermediate cooling stations. Moreover, as the separate return line does not have to be routed in the same cable trench as the cable itself the installation flexibility increases. For example, a serviceable length of 5 km is possible with a temperature increase of 5 K, a pressure drop of 10 bars so that a nominal pressure of 15 bars and a minimum pressure of 5 bars is possible in the superconducting cable, while in the separate return line, the pressure may be as low as 2 bars and the temperature increase by a further 3 K, without affecting the HTS cable further. This enables up to 10 km distance between the cooling stations for a compact cable system, and only one intermediate cooling station along a 15 km long cable circuit.
- The HTS tapes are optimized for power cables use. The tapes are single-sided coated and Cu-laminated HTS-tapes with a current carrying capacity of $I_{C,\mathrm{avg}}$ (3 mm, 77 K) = 163 A. The trapezoidal cross-section is optimal for wrapping with a good smooth surface fitting which enables low AC losses. Figure 9 shows the measured AC losses of a 3 m long cable sample of the SuperLink Project

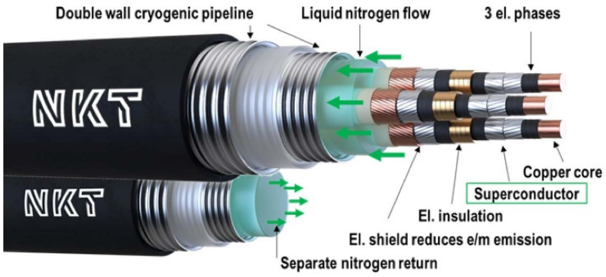

Figure 8. Cable design for the SuperLink Project in Munich [65].

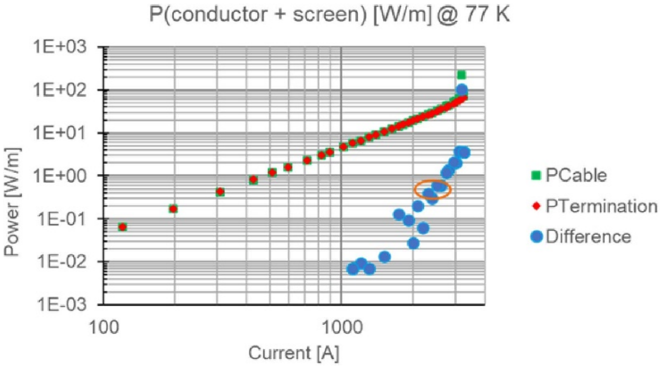

Figure 9. Measured AC losses of a 3 m long cable sample of the SuperLink Project in Munich. The losses are measured in the range of 1000 A to 3200 A (rms) and include both the losses of the phase conductor and the neutral screen conductor which also carries the full phase current and the losses of an end connector necessary for the experiment. 'Ptermination' shows the losses of this end connector alone. The 'Difference' shown in blue dots then includes only the losses of the conductor and the neutral screen. Unfortunately, NKT cannot presently disclose the I_c value and I/I_c ratio for this optimized cable design. Nevertheless, the authors believe that the low absolute values of the measured AC losses are of interest to the community within applied superconductivity.

in Munich. The AC losses include both the losses of the phase conductor and the neutral screen conductor which also carries the full phase current and are well below 1 W m^{-1} at the nominal current of 2600 A in the SuperLink cable design. The penalty factor of the cooling system is expected to add a factor of 10–15 to these losses, which is still significantly less than a corresponding conventional (XLPE-)system.

- The cryostat design is optimized and tested in evaporation tests and bending tests to reduce the thermal heat leakage. A low heat in-leak of 0.8 W m^{-1} was measured in a 12 m long cryostat sample.
- Besides the development of a classic electrical joint for the connection of two cable lengths, there is a joint for coolant, which can be used to increase the pressure and to reduce the temperature in the cable in order to realize long cable lengths.

The efforts in loss optimization and the chosen cooling architecture result to a design of a 15 km cable route. One cooling station at each cable connection point and just one additional intermediate cooling station along the cable route are necessary. The size of the intercooling station is limited to the size of a double-garage (about 130 m^3) or less to meet the limited installation space in urban area and does not necessarily need to be placed directly on the cable path. The system architecture of the cooling system is shown in figure 10.

Advances in science and technology to meet challenges

The consumption of electrical energy in large cities is increasing with the transition to energy conversion processes with reduced CO$_2$ emissions. The amount of required area power density in load centers needed for electric mobilization, electric heating and cooling can only be estimated currently. This challenging situation is accompanied by the existing problems when energy cable networks are to be expanded in cities: no more space and tightness under the pavement since many different other media are already laid there. At the same time, construction projects and their impact on the environment and traffic are under constant and increasing public scrutiny. HTS cables offer a suitable alternative to solve

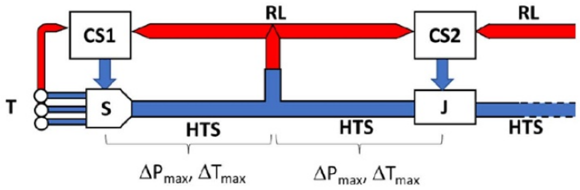

Figure 10. Cooling principle for the SuperLink Project in Munich [65]. Legend: T (Terminations), S (splitterbox, where the three conductors were separated), J (cooling joint, where cooling liquid is returned from one side and injected from the other), CS1 (cooling system at cable connection points), CS2 (intercooling system, second cooling system installed along the cable route), HTS (main serviceable cable length), RL (warm coolant return line).

many of these problems. They can be built with an extremely small cross-section, allowing one HTS cable connection to replace several conventional XLPE cable systems with increased energy transmission capacity. They even enable the energy transport on a lower voltage level. This also reduces construction costs and space requirements [66], which are particularly costly in densely populated areas with numerous utility systems and other infrastructure. Interaction with neighboring systems such as traffic and disruption to public life during construction is kept to a minimum [60]. Thereby superconductivity offers new possibilities in terms of grid architecture and grid management. Transmitting high currents instead of high voltages enables highly utilized power connections with minimal grid losses. The targeted use of individual HTS cables can efficiently reduce the stress of the existing (service aged) grid, which has a positive effect on the need for expansion, grid utilization and overall losses.

Concluding remarks

Superconductivity enables inner-city high-performance connections and positive effects in inner-city grid expansion, grid architecture and grid management. However, the necessary cooling system represents a new component in the grid, which increases the complexity of the system. Another important point is the economic advantage of HTS-cables. The predicted price-volume effects when HTS-cable become standard grid components, are likely to result in increasingly economic advantages, especially for areas of high energy density.

Acknowledgments

The collaborative project is being carried out by a consortium consisting of the network operator SWM, the cable manufacturer NKT Cables, the cooling technology and gas company Linde, the HTS conductor manufacturer THEVA, the Karlsruhe Institute of Technology and the South Westphalia University of Applied Sciences and is financially supported by the Federal Ministry of Economics and Climate Protection (BMWK).

6. Superconducting DC high power transmission lines

Keith McCullough

Eoin Hodge, SuperNode, Ireland

Status

The majority of superconducting power cable development and demonstration projects to date have been AC in application. AC superconducting cable technology has now matured to technology readiness level (TRL) 8 [67] and is operational in numerous grids globally, resolving capacity and resilience constraints in distribution grids [68]. IEC standard IEC63075 has been developed to govern their qualification and commercial type testing. Whilst DC superconducting cables are currently considered at TRL 6 [68], they can leverage the maturity and track record of the AC technology, quickly developing to commercialization and delivering game-changing impact to high-capacity transmission as we revolutionize our electric grids and decarbonize our energy systems through renewable sources [69]. Numerous DC superconducting cable demonstration projects have been undertaken globally as presented in chapter 4 of this roadmap.

Future cable developments of note are those currently under development as part of the Horizon Scarlet project, where Nexans is leading a work package to demonstrate a 1GW rated, ±50 kV, 10 kA REBCO DC superconducting cable [70]. Additionally, ASG are leading a work package to demonstrate a 500 MW rated, 25 kV, 20 kA LH_2-cooled MgB2 DC superconducting power cable [70]. Also of note, is the SuperRail project in Paris, comprising two 60 m long 1.5 kV–3.5 kA HTS DC cables being delivered by Nexans [71]. SuperNode will qualify a novel 500 MW rated, 100 kV DC HTS superconducting cable to TRL 6 by 2025, in accordance with a qualification program being certified by DNV [72].

Renewables energy systems (RESs) connections and DC power transmission have moved to standardize at 2 GW, 525 kV rated copper-XLPE based cable systems. However, with limited supply chain availability over the coming decade in HVDC cable and equipment manufacturing, significant bottlenecks are developing. AC superconducting power cables at high-capacity ratings incur AC losses inter alia that impacts their economical proposition, making DC superconductors preferable for the rollout of long-distance transmission. DC superconducting transmission cables can provide significant power capacity at reduced operating voltages, which reduces the size and cost of offshore and onshore substations [70]. An MVDC offshore system may also unlock equipment supply chain constraints presenting with current HVDC technology, facilitating an acceleration in high-capacity RES connections and meshed grids. Much of our future energy generation is due to be located remote to our population and industry demand centers, often in offshore wind clusters. DC superconducting transmission systems that are marine enabled, as part of an offshore MVDC system including WTG DC drivetrains, such as depicted in figure 11, will be required to connect and transmit bulk power from RES [70, 73].

More power dense cable systems operating at lower voltage reduces the right-of-way width required for onshore transmission paths, reducing public objection and delays to such critical infrastructure projects [74].

Current and future challenges

To realize these benefits and achieve widespread use in power transmission, DC superconducting cables need to scale beyond the capabilities of the current generation of the HTS cable technology. A multi-faceted performance improvement is required, addressing higher power capacities, longer transmission distances and reduced costs.

Transmission system integration

State-of-the-art power conversion systems are tailored for current capacities that typically result from copper XPLE cables, usually limited to circa 2000 A for a 525 kV transmission system [70]. A 2 GW DC superconducting cable-based system can operate at 10 kA and ±100 kV for the equivalent power capacity. A high-capacity MVDC transmission system can be enabled by the DC HTS cable which otherwise would be prohibitively expensive, requiring multiple copper cables [75]. Reconfiguration of DC substations to optimally integrate with high-current, medium voltage cables is required [70]. However, such network equipment is currently at low TRL and needs to be developed further [75]. Various feasible approaches around reconfiguration of modular multilevel converter (MMC) modules along with the associated switchgear has been proposed and may provide significant value from a system perspective [76, 77].

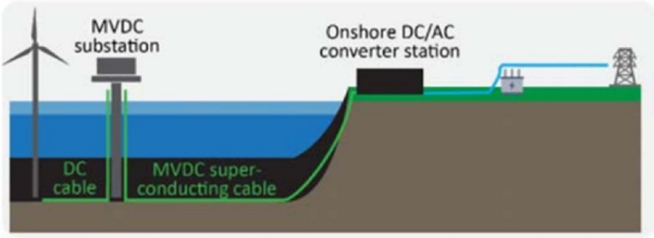

Figure 11. Power export through an MVDC Superconducting power cable for a DC Wind Array © [2024] IEEE. Reprinted, with permission, from [70].

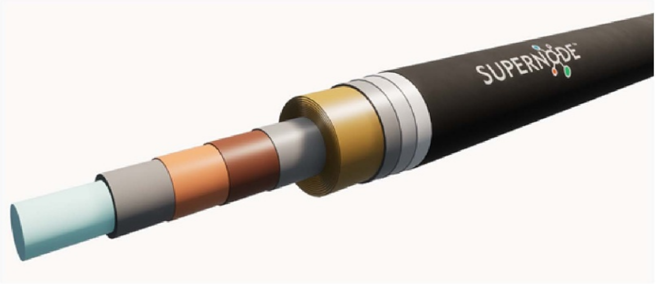

Figure 12. SuperNode's next generation DC superconducting power cable [72].

Cryostat technology

The current generation of HTS cables are configured in various architectures, but predominantly utilize corrugated stainless-steel cryostats to facilitate thermal expansion and contraction. A significant hydraulic penalty results which limits the application of the technology to long distances [73]. A smooth bore cryostat facilitates extension of the range between repumping stations to distances that would be more acceptable to customers. An example of such an approach is being developed by SuperNode, as depicted in figure 12. SuperNode's novel Inner Cryostat polymer technology satisfies thermal and mechanical stability requirements; their novel thermal insulation operates with a more robust soft vacuum regime; and their multi-layered Outer Cryostat system comprising a warm dielectric, delivers a total cable diameter of circa 150 mm for a 2 GW power capacity. SuperNode's simulations, independent accredited laboratory physical tests, and comparison to published data all confirm that for a given flow rate and inner diameter the smooth bore cryostat has around 1/3 the pressure drop per meter compared to the corrugated pipe. SuperNode plan to achieve a TRL of 6 for their cable technology in 2025 and in parallel to demonstrate their cable technology operationally in a National Grid test substation.

Cost

Cost remains a significant challenge to the widespread adoption of DC superconducting power cables. HTS tape costs remains a significant contributor to this with prices for scaled production of HTS tapes to supplying the SuperLink project in 2027 expected to achieve 50 € kAm^{-1} at 77 K, self field [78]. Longer term predictions for further tape price reductions are expected to be realized towards the end of the decade as more suppliers invest in and develop volume manufacturing facilities globally. Significant cost for long-distance applications is incurred from the stainless-steel cryostats. Alternative cryostat technologies that can be manufactured at scale will drive down costs. Lifetime vacuum integrity for a cable system, which has a distributed thermal envelope, is critical to ensuring required thermal performance can be maintained and the operating losses of the system are advantageous relative to copper-based cables. Industrial cooling technology is available commercially and scalable in modules of 40 kW capacity using Turbo-Brayton (TB) refrigeration units, with costs having reduced considerably as volume production has developed.

Operation & protection

DC superconducting transmission cables are dynamically operated, requiring active cooling system control, powering, monitoring, etc. These features present a challenge for power system operators who, being accustomed to simpler copper systems, lack experience in managing such a HTS system.

Preventative and corrective maintenance regimes need to be developed that achieve the availability needs of the transmission industry.

Standardization

Additionally, much work needs to be done promoting the merits of this technology to industry, regulatory and political stakeholders. Ultimately, a DC superconducting cable testing standard, equivalent to IEC63075 applicable to AC HTS cables is required to standardize development and implementation of the cables.

Advances in science and technology to meet challenges

System integration studies that leverage superconductor's current density to lower transmission system voltage and cost is an area of significant focus for various research groups and collaborative projects. Optimized power electronics architectures to accommodate increased transmission currents for high power capacities at voltages ranges from 25 kV to 100 kV have been proposed [76]. Protection and control of MMC integrated HTS transmission cables are being studied for application to high-capacity RES connections and meshed grids, with results promoting the system protection benefit that fault-tolerant DC HTS cables can provide in firewalling system fault propagation and easing breaking requirements on DC circuit breakers (DCCBs) [79]. DCCB technology optimized for integration with superconducting power cables is being investigated through the Horizon Mission project.

Cryostat materials, thermal and hydraulic performance, operational robustness and manufacturing processes are all currently undergoing significant research and development such that the constraints in technology developed for distribution applications can be scaled to address long-distance transmission markets [72, 73].

HTS tape costs have resumed a downward trajectory, with recent new entrants in China and the USA investing in volume manufacturing to drive costs down in anticipation of markets such as that of DC transmission maturing towards the end of the decade. Likewise, the established tape companies are investing in production capacity to meet the expected volume demand and cost targets for transmission.

Cooling technologies utilizing evaporative cooling and two-stage cooling are under development with the potential to extend the range between liquid nitrogen cooling refill or re-cooling systems, which would increase system robustness, reduce cost and increase customer acceptance.

Concluding remarks

DC superconducting transmission can be a game-changer for high-capacity grids and be a key enabler for a decarbonized electricity system. The technology is uniquely positioned with the potential to resolve the capacity challenges that present for long-distance, bulk power transfer and volume RES connection and transmission. However, numerous challenges remain for widespread commercial adoption of the technology, those of cost; volume manufacturability; network integration and control; reliability and availability; and the development of appropriate Preventative and Corrective Maintenance strategies. Operational experience and technical maturity of AC Superconducting power cables can be leveraged to accelerate the qualification timelines needed to match the ramp up in RES connections that will occur in the 2030s. As outlined, numerous innovations are under development to resolve the challenges that present for the technology in application to transmission; HTS tape supply and cost are improving; cooling technologies are advancing, materials and manufacturability innovations are being progressed rapidly.

An innovation gap exists in transmission technology which DC superconducting power cables can address. This is reflected in the increased support being expressed for the technology and its development across various European government and regulatory advisory bodies and projects, such as important references in the EU Grid Action Plan [80], EntsoE Technopedia [68] and the recent Horizon sponsored Ready4DC project [77]. Further support is required, particularly around provision of Pilot project opportunities to progress the technology to TRL 7 and beyond.

7. Superconducting overhead transmission lines

S Ishmael and M Luke

Veir Inc., United States of America

Status

Existing overhead power transmission lines use conventional resistive conductors operating at high voltage and low ACs to minimize power losses during delivery. Globally, electricity demand is rising due to the growth of emerging and established economies, increased electrification, and expanding heavy industry. In the United States, an estimated 97% of power lines are overhead and experience around 8% losses. Despite global growth in renewable generation capacity, grid congestion remains a barrier to integration of these clean energy sources into the grid. Many transmission pathways are already at or near capacity, with aging infrastructure operating well beyond it is designed lifespan, leading to worsening reliability. These challenges hinder progress toward carbon neutrality and are exacerbated by increasingly frequent extreme climate events.

To address these challenges, potential solutions include building new or reconductoring existing lines either using advanced conductors, or deploying underground transmission lines. The primary focus of these solutions is to enable high-capacity power at transmission level voltages (>69 kV). However, such projects typically face lengthy permitting processes, averaging of 7–10 years. In the US alone, an approximate 2600 GW of installed renewable capacity is awaiting grid connection, highlighting an urgent need for expanded grid capacity and reliability. Superconducting power transmission lines (SCTLs) offer a promising solution due to high power density and ability to carry the same amount of power in smaller rights-of-way (ROW). Advancements in cryogenic cooling technology have made overhead deployment of SCTLs feasible. A 2010 demonstration of a short distant, proof-of-concept overhead SCTL was constructed at Los Alamos National Laboratory (LANL) [81]. Overhead superconducting transmission lines (O-SCTLs) offer cost advantages over underground installations, with costs for buried lines estimated to be 4–14 times higher [82] and associated converter costs approximately 82% lower.

Building on the work at LANL, a Woburn, Massachusetts-based company, VEIR, is commercializing and accelerating the deployment of O-SCTLs. The anatomy of VEIR's O-SCTL solution is illustrated in figure 13. The components of the O-SCTL consist of (1) liquid nitrogen (LN2) generation or storage options; (2) cryogenic conditioning infrastructure including pumps; (3) pole-top termination units for resistive to superconducting connections (4) conductor assembly including the cryostat and HTS cable core; (5) pole-top heat exchangers for periodic re-cooling of LN2. The conductor assembly consists of a cryostat (vacuum jacketed pipes), the electrical cable manufactured using HTS material (referred to as a HTS cable core), LN2 cryogen (pressurized and continuously flowing along the line), and the suspension hardware including poles and hanging structures. The cryostat, a double walled tube filled with multilayer insulation (MLI), maintains the cryogen (liquid coolant) at a target temperature (77 K). The HTS cable core carries the electrical power.

The O-SCTL consists of three, single-phase AC lines, each operating at line voltage potential and utilizing the surrounding air for voltage insulation as in conventional overhead power lines. As an alternative to traditional resistive high-voltage transmission lines, O-SCTLs offer significantly higher power transmission capacities at any given voltage level. This technology allows for high-capacity power transmission, which was typically only achievable at transmission-level voltages, to be realized even at distribution-level voltages.

Current and future challenges

Superconducting cables for power transmission have achieved an advanced level of development, yet their widespread commercial adoption faces numerous challenges. While the primary benefit of these cables lies in the negligible resistive losses, especially over long distances, existing regulatory and political policies in many regions do not incentivize efficient transmission via loss reduction. As a result, the costs associated with losses are often borne by customers through operational expenses, hindering investment in energy-saving solutions. Policies and regulations that incentivize energy efficient transmission are necessary for driving the paradigm shift.

Existing incentives for adopting energy-saving technologies include cost savings including ROW land acquisition, installation, reliability, maintenance, expedited siting and permitting approval processes, and alleviation of congested power transmission corridors. Thus, O-SCTLs incentives represent an opportunity to address both technical and economic challenges.

Figure 13. Shows anatomy of an O-SCTL solution with one phase of a three single-phase line pictured. (1) liquid nitrogen (LN2) generation/storage; (2) cryogenic conditioning infrastructure; (3) pole-top unit (terminal) (4) conductor assembly; (5) pole-top unit (heat exchanger).

O-SCTLs face similar technical hurdles to underground SC lines, yet unique challenges present for overhead lines. First, O-SCTLs must adhere to safety standards for suspended lines, their supporting infrastructure, and must account for factors like ice loading, temperature fluctuations, wind variations, and other relevant conditions. Investigation into the applicability of existing installation, maintenance, and repair methods, and new methods required for in-field splicing and cryostat vacuum maintenance, are fundamental to implementation. Failure mode analysis is essential, encompassing various system failures (e.g. 3-phase fault to ground), ice-loading risks, lightning strikes, and the impact of uneven shading. Investigations are required to evaluate any risks associated with uninsulated and pressurized LN2 in suspended lines over long distances. O-SCTLs utilizing LN2 with open loop cooling will require CAP-EX and OP-EX cost evaluations to relay overall system benefits. Public acceptance is a critical aspect of implementing new technologies, often hindered by a fear of the unknown and a general lack of familiarity. This lack of awareness can lead to opposition or, often unnecessary, delays in adoption.

Furthermore, challenges common to both O-SCTL and traditional superconducting cables include minimizing AC losses, joints and termination techniques [83], developing efficient cooling techniques, and ensuring fault handling [15] and protection.

Non-technical barriers, particularly supply chain dynamics and the cost of HTS materials, influence commercialization efforts. Supply chain considerations include the availability of lightweight, long length cryostats and a scalable supply of HTS materials. While worldwide HTS production capacity is estimated to be 3000–5000 km yr^{-1} (12 mm width equivalent) [84], the number of HTS suppliers has grown in recent years, and material costs have declined. This scale up has supported early commercialization efforts, though further expansion is needed to fully realize the commercial benefits. Additionally, policy and regulatory changes are essential enablers [85] in the energy transition.

Advances in science and technology to meet challenges

Despite these challenges, breakthroughs in material science, cryogenic cooling, scalable manufacturing, and grid integration technologies (including protection and conversion systems) offer promising solutions. These advancements are driving progress in manufacturing, gaining global recognition as a critical solution for a sustainable future, and influencing policy changes and investment trends. In particular, the following developments are key to addressing challenges associated with O-SCTLs.

Distributed evaporative cooling:
Utilizing passive, open-loop cooling systems overcomes limitations to the removal of the heat generated by AC-operated cables. The approach as described [81] reduces the size and weight of cryostats. Together with a passive pole-top-mounted re-cooling system, this approach enables cost-effective, loss-minimized O-SCTLs at higher voltages and power levels up to 100 km between cooling stations.
Installation, Maintenance, and Repair:
An outdoor demonstration, depicted in figure 14, showcases a DC low-voltage O-SCTL. This demonstration helps build confidence in the installation, operation, and maintenance of an O-SCTL in an outdoor environment. Furthermore, in February 2024, VEIR entered into a funding agreement with the New York State Energy Research and Development Authority (NYSERDA) to support the deployment of an

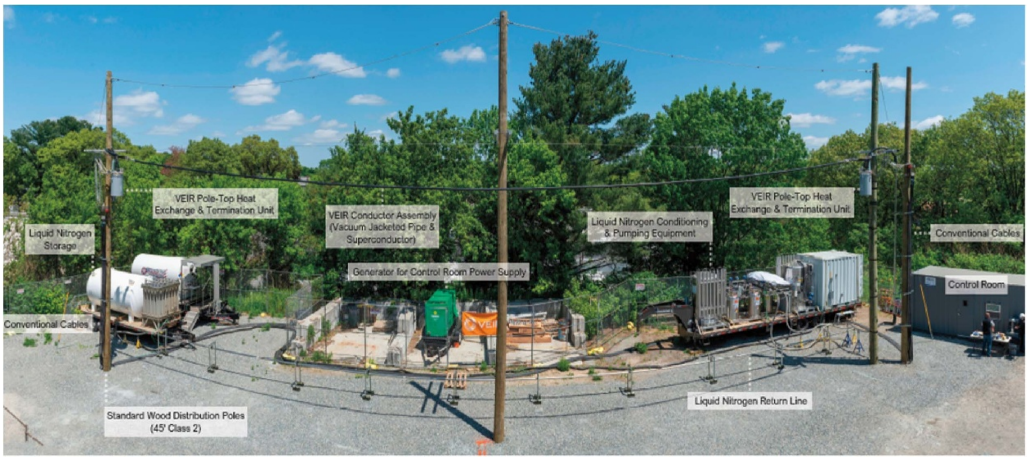

Figure 14. Shows a 30 m single-span suspended version of the O-SCTL demonstrated to understand withstand against outdoor environmental conditions and to utilize commercially available power line structures.

O-SCTL demonstration transmission line. The success of this NYSERDA-funded initiative will confirm to the feasibility of operating O-SCTLs with span lengths of 250 ft, validate the feasibility of installing and maintaining O-SCTLs, and demonstrate the economic and commercial viability of O-SCTLs.

Environmental Resilience and Impact:
An assessment of failure modes, encompassing system analysis, ice-loading considerations, and the impact of uneven shading on cryostats, underscores the environmental resilience of O-SCTLs. Moreover, O-SCTLs offer potential benefits in minimizing the expansion of power lines in Wildland-Urban Interface areas by employing smaller ROW corridors. Their design, characterized by no sag and higher melting points of conductor material compared to conventional conductors like ACSR, coupled with the quenching potential of a downed line filled with LN2, contributes favorably to their life cycle assessment and environmental impact compared to resistive high-voltage power lines.

Public Acceptance:
Public acceptance remains a critical aspect of integrating innovative technologies like O-SCTLs into existing infrastructure. Addressing the 'fear of something new' and lack of familiarity necessitates public education initiatives. Informative talks on LN2 properties, its common uses, and safe handling are essential to dispel misconceptions and alleviate general concerns. Utilities may require guidance on facilitating further education and expanding training to ensure the workforce is proficient in handling cryogenics, thus fostering greater acceptance and adoption of O-SCTLs.

Cost of HTS:
Significant advancements have been made in reducing the cost of REBCO, a key material in HTS technology, driven in part by demand from nuclear fusion applications. This reduction in cost per kiloampere-meter ($/kA-m) has paved the way for the entry of HTS technology into power transmission applications. Global investments [86] in HTS suppliers allowing for scale up in production [87] play a crucial role in meeting demand and are essential for the successful commercialization of HTS-based technologies like O-SCTLs [31, 88].

Concluding remarks

Globally, there is increasing recognition of the crucial role that power transmission plays in achieving carbon neutrality. Recent advancements in science, technology, and manufacturing have opened up opportunities for innovative solutions like O-SCTL to play a transformative role in addressing climate change. O-SCTLs offer distinct advantages, such as lower installation costs compared to underground, and options for a delivery of transmission level power with reduced ROW at distribution voltage requirements, or for increased power transmission (5–10 times) within the same ROW footprint at transmission voltages.

O-SCTLs present a unique opportunity to alleviate grid congestion and enhance power delivery in critical areas. They enable high-capacity power delivery into regions where grid bottlenecks limit renewable energy integration, streamlining interconnections and expediting clean energy deployment through shorter permitting processes. They may function as high-capacity tie-lines, strengthening regional interconnections and facilitating the efficient transfer of power between areas with surplus generation and regions with high demand, improving overall grid resilience. In dense urban environments, where voltage constraints and limited ROW restrict conventional transmission expansion, O-SCTLs provide a viable solution by delivering more power within the same footprint, ensuring reliable electricity supply to growing loads.

Sustainable initiatives, aimed at attaining carbon neutrality through net zero energy production and consumption, are driving the urgency to adopt transformative solutions like O-SCTLs. Rapid resolution to these challenges is critical to the success of a sustainable earth.

8. Superconducting cables for dc distribution for electric aircraft propulsion

Emelie Nilsson[1], *Jean Rivenc*[2], *Jean-Francois Rouquette*[1], *Ludovic Ybanez*[1], *Matteo Tassisto*[1], *Frederick Berg*[3], *Souhaib Boukayoua*[1], *Antoine Delarche*[1], *Francois Dunoyer*[1], *Camille Chaper*[1], *Swapnil Kharche*[1] and *Jeremie Monin Baroille*[1]

[1] Airbus UpNext SAS, Toulouse, France
[2] Airbus SAS, Blagnac, France
[3] Airbus Defense and Space, Ottobrunn, Germany

Status

Liquid hydrogen fueled electric aircraft is a possible enabler to reduce the carbon footprint of aviation [89]. As the liquid hydrogen is stored at a temperature around 20 K, it can be used as a cold source to cool electric components which significantly decreases their resistance. The use of superconducting cables and electrical components is an opportunity to increase efficiency at high power which could result in a more efficient, compact and lighter electric propulsion system. In 2021 Airbus UpNext launched the ASCEND with the objective to demonstrate the potential and feasibility of a cryogenic and superconducting powertrain as a breakthrough electric propulsion solution for future electric aircraft [90]. The project included the development of a 10 m long superconducting DC link table 4, consisting of two poles of CORC® cables with 24 REBCO tapes each designed for nominal current of 1700 A and 300 V, and conduction cooled current leads cooled with flowing subcooled liquid nitrogen [41]. The cables are housed in a Nexans Cryoflex stainless steel cryostat. The proven efficiency, flexibility and light weight has convinced Airbus to develop the technologies further and push for the necessary adaptation to aircraft constraints.

For the 500 kW powertrain, a rather low operating voltage of 300 V was chosen. Operating voltage below 1000 V will significantly simplify the installation and reduce the constraints on the dielectric insulation. Using superconducting cables with high current density enables high power application without increasing the voltage operating point. The advantage of superconducting cables is that no power dissipation occurs in the superconducting material itself. Losses at the thermal interfaces are inevitable, as losses will be generated in the copper current leads that link the power source at room temperature to the superconducting cables in their cryogenic environment. The losses in a conduction cooled current lead are typically $\sim$50 W kA^{-1} at an interface between room temperature and boiling liquid nitrogen [91]. On the downstream end of the DC link, the superconducting cables are connected to a MCU. The MCU of ASCEND is cooled by gaseous LN2 and operates at a temperature of 100 K. Therefore, the losses on this side are even lower than on the side of the main current lead. The output of the MCU is connected to a 2 m long superconducting three-phase AC-link, with nominal operating current of 1800 Arms at a frequency of 500 Hz. The AC-link is connected to an electric motor. The layout of the powertrain is presented in figure 15. The efficiency of the superconducting DC link in the operating range of the ASCEND demonstrator at nominal power is >99.9%. Figure 16 shows the assembled DC and AC link.

The superconducting DC cable can act as a protection in overcurrent scenarios, for example due to a short circuit between the positive and the negative pole or faults at equipment level. If designed properly, the DC cable may act as a fault current limiter as its impedance increases when the superconducting tapes transition from superconducting to resistive state [92]. The superconducting tapes are electrically insulated from the aluminum core, such that the current will be redistributed from the REBCO layer to the copper stabilizer of the tapes when the critical current is exceeded. This feature may protect the powertrain and the downstream components, in particular the motor control unit and the electric motor, which are sensitive to overcurrents that can be on the order of ten times the operating current.

In ASCEND the superconducting cables were designed to limit the current in the system below 5 kA within 10 ms [92]. Lab tests showed that an electric field of 15 V m^{-1} was developed during overcurrent tests.

Current and future challenges

The electrical performance of superconducting cables at 500 kW has been demonstrated in ASCEND. Due to the strong dependence on temperature, design of superconducting cables with even higher carrying current is fairly straightforward. If a cold source is available on the aircraft at around 20 K, it is possible to operate the cables at temperatures well below 77 K, which increases the carrying current per cable significantly. This feature is an opportunity for scalability of the DC link to multi MW class applications without much penalty

Table 4. Design parameters and figure merits of the DC bus of ASCEND.

	Value	Unit
Conductor layout	CORC® with 24 Superpower SC4050 tapes on aluminum core	
DC cable design temperature	67–70	K
Critical current at 77 K	3000	A
Nominal current	1700	A
Nominal voltage	300	V
Current lead heat load (Per lead)	100	W
Max short circuit current	6800	A
Short circuit duration	10	ms
Withstand voltage	2000	V
Length of the DC link	10	m
Cryostat outer diameter	44	mm
CORC® cable weight (two poles)	0.286	kg m^{-1}
Cryostat weight	0.8	kg m^{-1}
Coolant weight	0.2	kg m^{-1}
Total weight/meter of DC link straight section	1.3	kg m^{-1}

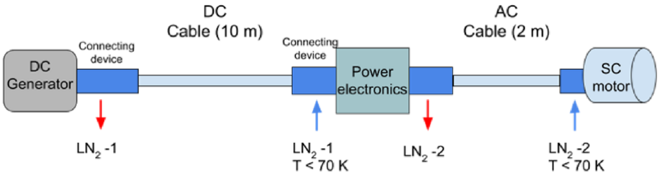

Figure 15. Schematic view of the ASCEND demonstrator. The links are cooled with flowing liquid nitrogen, the inlet and outlet of the cooling circuit is referred to as LN2-1 for the DC link, and LN2-2 for the AC link.

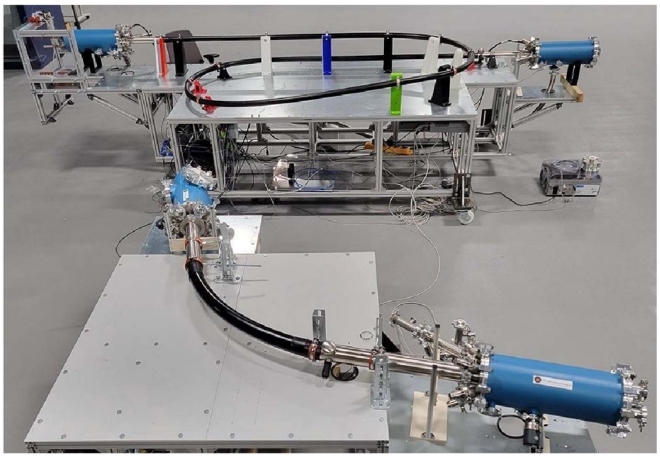

Figure 16. The superconducting DC (in the background) and the AC link (in the foreground) in Airbus Electric Aircraft Systems House, Ottobrunn during integration in the testbench in 2023.

on the weight or volume of the cables, and without requiring an increase of the operating voltage.

The advantages and potential of using superconducting cables in the DC link of an electric powertrain have been demonstrated. The design target of the superconducting DC link in the ASCEND project was reached. The weight of the cable section is 1.3 kg m^{-1} (including conductors, coolant and cryostat), which is better than the initial target of 2 kg m^{-1}. In addition, the DC link can act as a fault current limiter which protects the entire powertrain in case of overcurrent. The advantage of this solution is reduction of weight, volume and complexity as the FCL and the power transfer function can be merged into one single component. To reach the suitable impedance to limit the current during a fault, the distribution must be of a certain length, and/or a higher electric field per meter must be targeted. Cables developed with CFD tapes could provide a solution even for future designs of a DC distribution with shorter length and/or higher operating voltages [93]. The ASCEND demonstrator shows that a superconducting DC link has many advantages: high efficiency, compactness (the outer diameter of the cryostat is 44 mm), flexibility (the bending radius is 35 cm) and lightweight. The flexibility and weight of the cryostat can be further adapted to the aircraft environment by developing customized components for the application. The main challenge is the weight of the connecting devices which house the current leads. These parts are rather bulky compared to the superconducting cable, as they consist of off the shelf components in stainless steel and copper. In addition, the current leads are housed in a vacuum space, relying on active vacuum pumping which adds additional constraints and complexity to an aircraft embedded system.

Another important challenge is the operation of the superconducting cables and the systems taking into account the overall operational and environmental constraints in an aircraft environment. Efforts must be made to assess the performance of superconducting tapes, superconducting cables including terminations and dielectric insulation under vibration and variable cooling availability along the mission profile. Also the impact of repeated thermal cycles on the components shall be assessed.

Advances in science and technology to meet challenges

Superconducting DC link prototypes will be developed in a laboratory environment, with components undergoing fatigue, aging and vibration tests. The next generation of a superconducting DC link will likely be cooled with a gaseous coolant (for example gas helium) to reduce the weight compared to liquid nitrogen and avoid phase transition from liquid to gas that might lead to overpressure in the cryogenic enclosure. A gas helium cooled DC link has recently been developed and tested [94].

The design and performance of superconducting links in laboratory environments are well mastered. The next step will be to mature and adapt the superconducting DC bus components to support the installation constraints in an aircraft, as well as the exposure to vibrations. Mechanical spacers and supports to prevent chafing which could degrade the performance of the cables or cause failure of the dielectric between poles or the pole to cryostat are currently under development. Vibration tests should be performed on superconducting REBCO tapes, cryolines, dielectric material, terminations, joints etc. The exposure to thermal cycles should be investigated and technologies should be adapted to the modes of operation in the aerospace industry.

Concluding remarks

A first 500 kW superconducting DC link was developed at Airbus within the ASCEND project. The compact, lightweight, and flexible DC cables were designed with fault current limiting functionality to protect equipment from excessive over-currents. It is a first proof of concept that paves the way for further optimization and adaptation to the aircraft environment. The high current density and the scalability of the power with very little impact on weight, volume and complexity makes superconducting cables promising in the development of fully electric aircraft in the multi MW class.

Acknowledgments

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9. High current superconducting busbars for industry

Carsten Räch, Wolfgang Reiser, Stefan Huwer,
Claus Hanebeck and Peter Abrell

Vision Electric Super Conductors GmbH, Morlauterer Straße 21, 67657 Kaiserslautern, Germany

Status

In many areas of energy intensive industry an enormous demand for electric energy is needed. The distribution via copper or aluminum busbar systems requires high material usage, transport and installation costs as well as substantial space requirements. Additionally, rising electricity costs over the last few years has impacted the viability of high current applications significantly. Every MWh that is not lost in transit does not need to be generated and transport losses of electricity are related to the electrical current. In energy intensive industries an increasing number of applications are based on high DC. Applications like chlorine, copper or zinc electrolysis as well as aluminum smelters need DC ranging from 10 kA up to 600 kA. Also, with the increasing power consumption of data centers, low voltage DC system architectures are investigated with amperages of 15–200 kA. The distribution length typically varies between 50 m and 1.500 m.

Recently, HTS busbar systems are able to conduct DC with extremely high densities of more than 50 kA cm^{-2} and zero electrical losses. Therefore, significantly less conducting material is needed compared to a conventional busbar system. As a result, HTS-technology requires less space and system weight is greatly reduced, which simplifies the installation in restricted rooms. With liquid nitrogen (LN_2) as cooling, standardized refrigeration systems can be used, which contributes to lower operational costs and higher reliability.

Several research and development projects worldwide have established HTS DC. In 2011 the world's first HTS DC cable in a commercial/industrial setting was installed in an aluminum electrolyze plant [95] while 2014 the world's first superconducting HVDC cable was energized on Jeju Island in Korea [96]. The European Best Paths project developed the first-ever superconducting HVDC cable with a transmission capacity of 3.2 GW [97]. However, the amperage of these projects does not exceed 20 kA and thus remains below the operating current of modern energy intensive industries. Also, the flexible cable-type approach for HTS DC transmission is difficult to manage for higher currents. Fixed, rigid superconducting busbar installations are an alternative option for such systems. This allows the use of many superconducting tapes in a small cross-sectional area. Within the German government funded project 3S (SupraStromSchiene) a 20 kA HTS busbar prototype was installed and tested for use in a chlorine electrolysis in Germany [98]. The follow-up projects, DEMO200 [57, 99] and SuprAl [100], aim to demonstrate a modular, superconducting 200 kA DC busbar system for an aluminum smelter and first tests are showing promising results.

Current and future challenges

HTS DC cables have been successfully demonstrated, while first industrial projects for high current HTS busbar systems are ongoing. The main components of such a superconducting busbar system, as seen in figure 17, are:

- Current leads: They connect the 'cold' superconducting system to the 'warm' standard electrical equipment.
- Busbar elements: They consist of cryostat and an arrangement of multiple superconducting tapes. The superconducting busbar elements result in a modularly assembled line, with the option of creating compact curves.
- Cooling system: Consists of cryocooler and cryogenic pump.

For high current systems, multi-conductor concepts are frequently used, in which multiple Stack, CroCo (Cross-Conductor) or CorC (Conductor-on-round-Core) layouts are bundled together to one superconducting busbar. Up to several hundred HTS tapes can thus be combined in one multi-conductor concept. An optimal arrangement of conductors is mandatory to reduce material costs and space requirements. Other challenges include thermal and Lorentz forces, which need to be absorbed by the system. AC-losses due to current ripples also need to be considered.

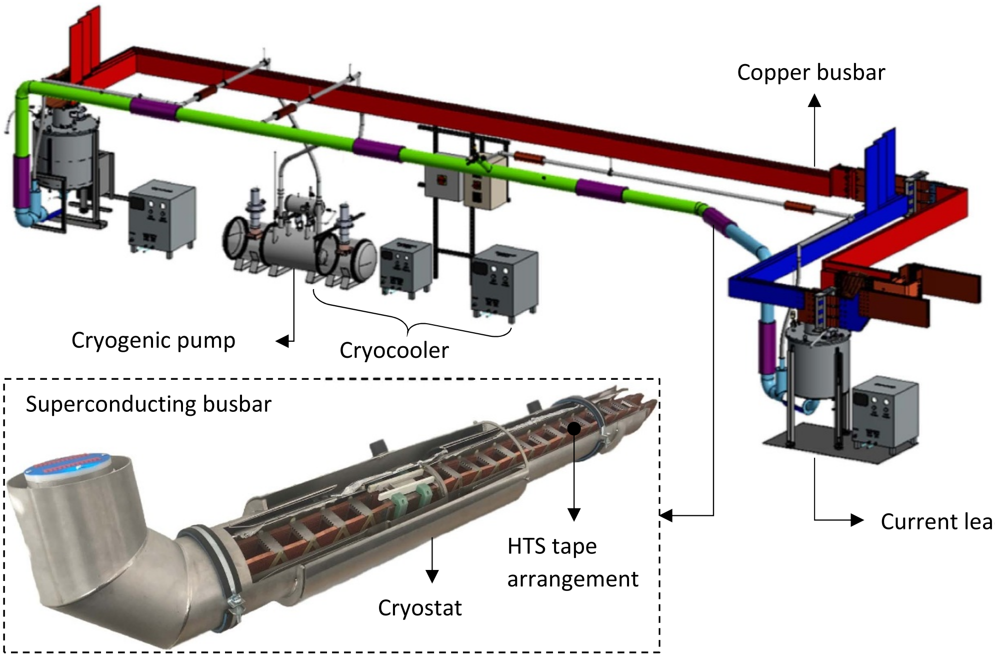


Figure 17. Superconducting busbar system for 20 kA next to a comparable copper busbar system.

To connect multiple busbar elements, a low resistance joint is necessary. These joints must be suitable for construction sites, as the connection of several elements happens on site. Joints for 20 kA busbar systems are designed with contact resistance below 10 nΩ.

In superconducting systems with short lengths and very high currents, the resistive current leads represent a major source of losses. Therefore, an efficient current lead design, for example a multi-staged current lead, is important to realize an overall efficient system. Another forthcoming approach to enhance efficiency is the use of controllable cryocoolers as well as the use of a cryogenic mixed-refrigerant cycle in the current leads.

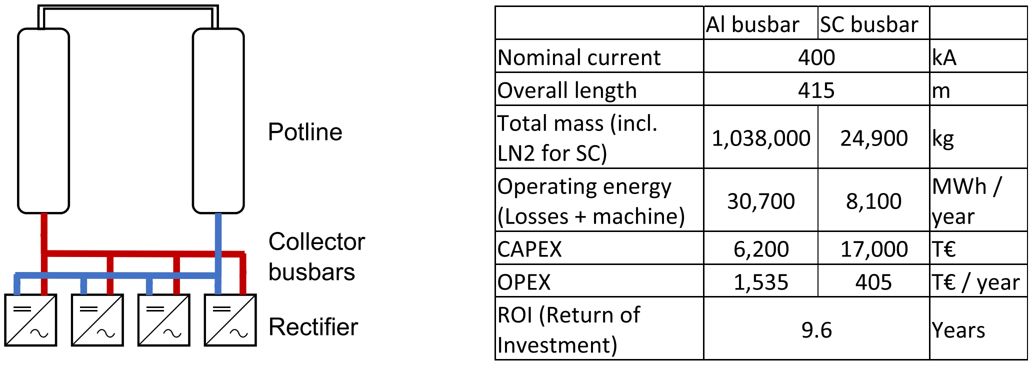
In addition to busbar systems with HTS tapes, new concepts with MgB_2 wires are currently being developed. MgB_2 wires are commercially available in long length and represent a low-cost alternative for HTS tapes. The High-Luminosity LHC at CERN, will feature superconducting links comprising of 19 MgB_2 cables twisted together, to transfer a DC of about 120 kA [101]. However, the operating temperature of MgB_2 is 20 K and must be cooled by Helium or liquid Hydrogen. Such cooling concepts are more expensive and more difficult to implement.

Advances in science and technology to meet challenges

While there have been successful demonstrations of superconducting busbar systems in the industry, there are still just a few systems with currents up to 20 kA and no systems with currents above that. Within the 3S and DEMO200 projects, two prototypes were installed in a relevant environment, achieving a TRL of six. But a higher TRL will be needed to convince industrial companies to invest in a new technology. In addition, it must be ensured that fault case scenarios have almost no impact on the operating line. Projects, like the 200 kA busbar system for an aluminum smelter, will increase the TRL and remove the barriers for new projects.

The cost of superconducting material is also a main challenge holding back large-scale industrialization and utilization of superconducting technology. A study illustrated the economic performance of four possible superconducting busbar applications in the aluminum industry [102]. In each case, the higher CAPEX of the superconducting system as well as the lower OPEX, compared to a conventional busbar system, resulted in a return of investment between 3 to 10 years.

In figure 18 one of the four use cases is summarized, whereby a busbar system connects several rectifiers with the first and last pot in a cell room. The operating current is 400 kA and the overall length for the main busbar is 415 m, data taken from an existing plant. The standard material for such high current busbars is aluminum (Al busbar) due to the low-cost ratio compared to copper systems. However, the disadvantages are a larger system volume and weight. A comparable superconducting busbar system (SC busbar) carries the high current without electrical losses as well as significantly less volume



	Al busbar	SC busbar	
Nominal current	400		kA
Overall length	415		m
Total mass (incl. LN2 for SC)	1,038,000	24,900	kg
Operating energy (Losses + machine)	30,700	8,100	MWh / year
CAPEX	6,200	17,000	T€
OPEX	1,535	405	T€ / year
ROI (Return of Investment)	9.6		Years

Figure 18. Comparison of equivalent aluminum and superconducting collector busbars for an aluminum cell room. Reproduced from [102], with permission from Springer Nature.

and weight. Despite the high investment costs, the calculated example indicates a payback period below 10 years, because of the low operational costs.

Moreover, a reduction of investment costs will be expected in the next few years, as the cost for HTS tapes declines because of an increasing supply of tapes for large superconducting projects worldwide. Also, copper and energy costs are rising, which increase the investment and operating costs for conventional busbar systems.

Concluding remarks

An increasing number of applications based on high DCs as well as rising copper prices and energy costs require an innovative new method for power transmission and utilization in energy intensive industries. Superconducting busbar systems are technically feasible and an economically advantageous solution. Reduced costs for superconducting tapes are expected in the next few years and low operating costs are already providing a short paybackperiod.

Several DC projects with currents up to 20 kA have demonstrated the feasibility of superconducting cable and busbar systems. First projects for higher currents up to 200 kA are underway and showing promising results.

Still, a higher TRL is needed for convincing industrial companies to invest in a new technology. More industrial projects are necessary to demonstrate the feasibility of superconducting busbar systems in an operational environment and rise the acceptance of an innovative technology.

10. The Ishikari cable for power supply of data centers

Noriko Chikumoto

The University of Osaka, Osaka, Japan

Status

The use of HTS cables in DC transmission is attractive because there is no AC loss, thus maximizing the benefits of zero resistance of superconductivity. Since the energy dissipation is negligible in the DC cables, the energy consumption for maintaining the low temperature of the superconductor appears as the main source of the transmission losses. Therefore, the refinement of the efficiency of thermal insulation is an obvious way to improve the economic performance of superconducting transmission line.

Generally, the HTS cables are installed in a cryogenic pipe for thermal insulation and cooled by the flow of a coolant, such as liquid nitrogen, to achieve superconducting state. The current characteristics of the cable depend on the temperature of the coolant and the temperature of the coolant should be maintained below that required in the specification. In general, the temperature rise of the coolant, ΔT [K], can be written as:

$$\Delta T = \frac{qL}{\nu A \rho C_p} \tag{1}$$

where, q [W m^{-1}] is heat load, L[m] is the length of the cryogenic pipe, ν [m^3 s^{-1}] is the flow velocity of the coolant, A [m^2] is the cross-sectional area of pipe, ρ [kg m^{-3}] is the density of the coolant, C_p [J kg^{-1} K^{-1}] is the specific heat of the coolant. Therefore, the flow rate of the coolant should be high enough to limit the temperature rise along the cable.

Another factor to consider is the pressure drop due to friction between coolant and the inner surface of cryogenic pipe and between coolant and the cable surface during coolant flow. The pressure loss, Δp [N m^{-2}], can be written as:

$$\Delta p = f \frac{L}{D_h} \frac{\rho \nu^2}{2} \tag{2}$$

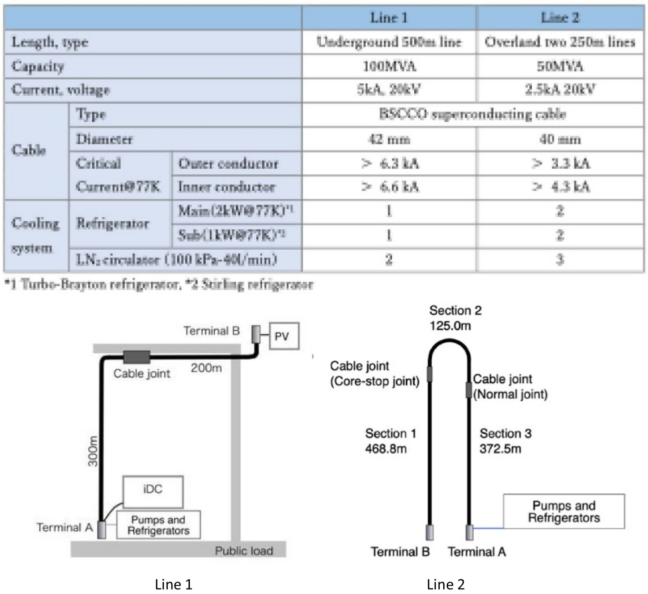
where f is a friction factor, D_{h}[m] is the hydraulic diameter. Therefore, it increases as in proportion to the square of ν. It is important to mention that the magnitude of this pressure drop determines the specifications of the pump used for circulation. Therefore, it is necessary to design the pipe diameter, pipe surface shape, etc, to minimize this pressure drop as much as possible.

Other important issues include mitigation of thermal stresses on cables during cooling and temperature rise, cable connections, etc.

Current and future challenges

The Ishikari Project was planned with the main objective of developing and verifying technologies to address the issues described above in long-distance DC cable systems. It was conducted in Ishikari, Hokkaido, Japan, from FY2013 to FY2016, and two power lines had been installed: line 1 connects a photovoltaic power plant and an internet data center by a 500 m underground cable (5 kA, 20 kV, 100 MVA) for practical use, while line 2 with 1000 m cable (2.5 kA, 20 kV, 50 MVA) for verification tests (figure 19) [103]. To ensure stable circulation of coolant over long distances, it is necessary to construct a system with sufficiently low heat penetration through the cryogenic pipe and a low friction coefficient. As for the reduction of heat penetration, two types of cryogenic pipes, shown in figure 20, were examined. In addition, straight insulating tubes instead of conventional corrugated tubes was used to reduce the tube friction coefficient. The normal-type cryogenic pipe was installed in line 1 as well as sections 2 and 3 of line 2, while radiation shielded type was in section 1 of line 2. The heat leak per unit length for the cable pipe and the return pipe, evaluated in the cooling test of line 2, was about 0.03 W m^{-1} and 0.85 W m^{-1}, 0.95 W m^{-1} and 0.52 W m^{-1}, 0.82 W m^{-1} and 0.46 W m^{-1}, for sections 1–3, respectively (at the outer pipe temperature approximately −3 °C) [104]. We consider that very low heat leak at section 1 of line 2 is owing to the radiation shield. We also measured the pressure drop during the circulation of LN_2 to be 11 kPa and 18 kPa for the cable pipe and for the return pipe with a distance of approximately 1000 m, respectively, at the flow rate of 32 l min^{-1} [104]. Note that these values are much smaller than reported values [105–110].

As for the cooling system, we used a closed-cycle liquid circulation cooling system in which liquid nitrogen is used as the coolant. A schematic illustration of the cooling system for line 2 is shown in



			Line 1	Line 2
Length, type			Underground 500m line	Overland two 250m lines
Capacity			100MVA	50MVA
Current, voltage			5kA, 20kV	2.5kA 20kV
Cable	Type		BSCCO superconducting cable	
	Diameter		42 mm	40 mm
	Critical Current@77K	Outer conductor	> 6.3 kA	> 3.3 kA
		Inner conductor	> 6.6 kA	> 4.3 kA
Cooling system	Refrigerator	Main(2kW@77K)*1	1	2
		Sub(1kW@77K)*2	1	2
	LN_2 circulator (100 kPa-40l/min)		2	3

*1 Turbo-Brayton refrigerator, *2 Stirling refrigerator

Figure 19. Layout and specification of the cable system of Ishikari project. © [2016] IEEE. Reprinted, with permission, from [103].

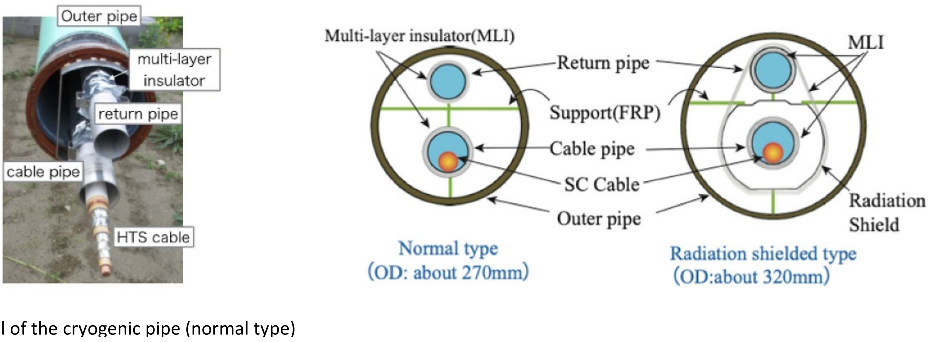


Figure 20. Structure of the cryogenic pipe installed in line 1 and 2 of Ishikari project. © [2016] IEEE. Reprinted, with permission, from [103].

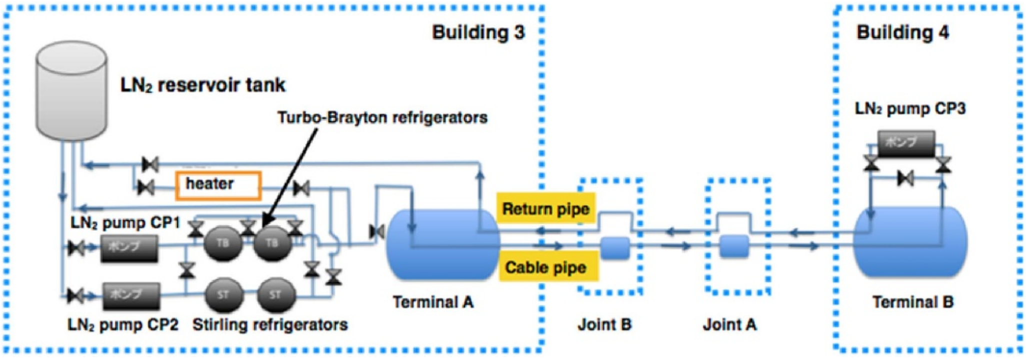


Figure 21. Schematic diagram for the cooling system.

figure 21. The cooling system is equipped with three LN_2 pumps, two 2 kW-class TB refrigerators (Taiyo Nissan Sanso Co.), and two 1 kW-class Stirling (ST) refrigerators (AISIN). The TBs were used as the main refrigerators, while the STs were deployed as a backup for recovery after a short power outage or in case of TB failure, to ensure the redundancy.

The average total power consumption of the cooling system in line 2 was 118.1 kW, where 45.3 kW and 23.6 kW for TBs, 48.9 kW for chiller of TBs, 0.33 kW for LN_2 pumps [104]. On the other hand, the average total heat load was about 2.6 kW, of which heat load of the cooling system was estimated at 0.4 kW. Since the cooling power of TB at 70 K was about 2.1 kW, the 1st TB at the upper stream of cooling system was in a full-load operation against 2.6 kW total heat load. Then residual heat load, which exceeded the cooling power of 1st TB, was cooled by 2nd TB, resulting in a partial load operation. This is the reason for the difference in the power consumption between two TBs. It also needs to be mentioned that the power consumption of the chillers was about 40% of the total power consumption. The power required for the coolant of the refrigerators should also be considered to estimate the total efficiency of the cooling system. Therefore, the choice of refrigerators with appropriate cooling capacity and disuse of chillers could increase the system efficiency.

On the other hand, in the application of superconducting cables to data centers, the proportion of the heat load at the terminal current lead in the overall heat load is larger due to the short cable length, and this must also be considered. In line 1, the measured heat load at terminal due to 5 kA current load was about 280 W/terminal, corresponding to about 28 W kA^{-1} with usage of so-called Pertier current lead [111].

Advances in science and technology to meet challenges

The above-mentioned factors include reduction of heat load and pressure loss in cryogenic pipe, reduction of heat load at the terminal, and improvement of COP of refrigerators in the feasibility of DC power transmission systems. The technical issues and prospects for each of these items are summarized below.

(1) **Reduction of heat load at cryogenic pipe**: Recently, Watanabe *et al* [112] reported on the portions of the radiative heat transfer and the conductive heat transfer in the total heat load, by analyzing the temperature dependence of heat load. This kind of approach may be useful for optimizing the structure of cryogenic pipe to reduce heat load. He reported the portion of the conductive heat transfer is 28% of the total heat leak at 20 °C for return pipe of radiation shielded type of cryogenic pipe. One very important element in thermal insulation is the MLI. Recently, various types of MLI with different structures have been developed and their thermal insulation performance has been improved. We believe that the thermal insulation performance can be further improved by employing the most appropriate MLI.

(2) **Reduction of pressure loss**: Although the use of straight pipes is effective in reducing friction loss, corrugated pipes have been widely used because of the disadvantage of less flexibility in installation compared to corrugated pipes. Here we would like to show the importance of reducing friction loss by comparing its effect in 1 km and 10 km cables. If the amount of heat penetration per unit length remains the same, the coolant must flow at 10 times the velocity in the 10 km cable to meet the allowable temperature rise ΔT for the cable. From equation (2), the pump discharge pressure required to achieve this in 10 km cable is 1000 times higher than that in 1 km cable. Furthermore, the waterpower, given by multiplying the discharge pressure with the flow rate, becomes 10 000 times greater, and the resulting heat load becomes not negligible. This problem can be avoided by shortening the distance between cooling stations, but this is not economical. In the Ishikari project, we have shown that using a straight pipe, the current pumps (discharge pressure: 0.1 MPa) can provide sufficient cooling up to a cable length of about 20 km. It will be necessary to consider a pipe structure that mixes the advantages of straight pipes and corrugated pipes to flexibly accommodate installation, etc.

(3) **Reduction of heat load at the terminal:** One of the unique features of the Ishikari system is the use of so-called Peltier current leads (PCLs) [103, 111, 113], namely 'active self-cooled' current lead, at the terminal to reduce the heat load. As mentioned previously, we succeeded to reduce heat load compared to conventional copper current lead. The problems with PCLs are that the current direction is limited to one direction and a heat removal mechanism is required. One issue that must be considered in the design of terminals is the transmission voltage. In the case of Ishikari, the voltage is 20 kV, and PCL has been confirmed to withstand 20 kV. However, higher voltage classes have not yet been confirmed.

(4) **Improvement of COP of refrigerator:** Considering that the upper limit of the COP of a refrigerator is the Carnot cycle efficiency, which is further multiplied by the mechanical efficiency, the maximum COP is considered to be about 0.1 for the difference between room temperature and liquid nitrogen temperature. COP of 0.08 was already achieved by Mayekawa Corporation in the

Brayton cycle refrigerator [114], which is installed and tested for long term operation [115]. Further reduction of COP could be achieved, for example, by using LNG for cryogenic heat.

Other issues: In addition to the above cooling-related issues, cable-related issues include thermal stress handling and cable joint. In Ishikari, thermal stress was handled by moving the terminals and deforming the cables so that they become helical at room temperature in advance [103]. However, it is necessary to verify whether this method can be applied to longer distance systems. As for joint, we adopted two types of joints, so-called core-stop joint and normal joint. But for both cases, about two weeks were required for on-site joint construction. In the actual system, it will be necessary to develop a technology that allows for easier way.

Acknowledgments

The Ishikari project was supported by the Japanese Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO). We are grateful to all the member of R&D partnership for Ishikari Superconducting DC power Transmission System (I-SPOT) for their participation, help, and discussions concerning this project.

11. The potential and status of superconducting railway cables

Jean-Maxime Saugrain and Arnaud Allais

Nexans, Paris, France

Status

In the context of energy transition from fossil to electric mobility, railways are expected to play a major role. One of their big benefits is to give fast access to city centers for mass transports. The corresponding increase of train traffic expected in coming years means more power to feed the catenaries and more power to the substations. The challenge behind this expected evolution is the already very constrained right of ways around railways stations in large cities areas. Indeed, new right of ways to be used for additional power supply involve usually very disruptive and complex civil works due to the presence of old constructions and other existing sensitive networks for water, electricity distribution or telecommunication. At the same time, existing installations and right of ways dedicated to railways can become locally saturated (see figure 22) and the use of conventional technologies based on additional resistive cables is limited due to the thermal impact on the environment and their own derating. Superconducting cables are then the only option to bring, through the existing rights of ways, the increasing amount of energy required by the train traffic evolution. The SuperRail project [71] illustrates this superconducting cable application. It consists in the development, manufacturing, installation and long-term operation of a HTS DC cable system for railway applications. Its main objective is to reinforce the power supply of the Montparnasse Train station in Paris with two superconducting cables able to carry each up to 3.5 kA at 1.5 kVDC (see figure 23). The total carried power of the two cables during train represent 5 MW in steady states and 10.5 MW for inrush current during train acceleration. The total cold power is 1.7 kW@67 K including the cooling system losses representing a power consumption of less than 100 kW including chillers.

Considering longer distance system in kilometric ranges, the superconducting system have been studied in Japan since 2013 [116] to allow more efficient energy management in a 1500 VDC network. A summary of the different experimental approaches conducted in Japan railways until 2020 [117] confirms the benefit of superconducting system to reduce the voltage drop and increase the net energy efficiency taking in account the consumption of the cooling system in the superconducting cable system.

Current and future challenges

Actual challenge for retrofitting projects is mainly to develop very compact and flexible superconducting cables in order to bring more and more power in the existing city rights of ways. The compactness is already brought by the high current density capacity in HTS tapes at liquid nitrogen temperatures and could be even improved in the future with higher performance of superconducting tapes at lower operating temperature by using other types of cryogens such as liquid hydrogen.

The improvement of the superconducting cable flexible cryostat in term of volume and thermal losses is also a major objective to reduce required rights of ways but also real estate in substations. For relatively short lengths, most of the system losses are coming from the terminations [118], and considering several kilometers, the size and power of the cooling system can be greatly reduced with higher performance flexible cable cryostats.

Another aspect specific to railways infrastructure is the very high level of fault current due to the direct connection with the transmission network. The actual strategy is to have a fault-tolerant superconducting cable but the use of fault current limiting properties of superconductors could be envisaged. The challenge of introducing DC fault current limiters, integrated or not in the cable, is to withstand the high level of the fault power and to keep at the same time the efficiency of the existing DC breakers to protect the installations.

The effects of introducing superconducting cable technology in railway networks should also be further investigated as it has a potential strong impact on the whole grid due to its very low impedance, advantageously used for reducing voltage drop on long distances. New approach of the railway grid management could emerge with such evolution [119].

Advances in science and technology to meet challenges

The continuous improvements of HTS tapes in terms of current carrying capacity, length and homogeneity are the core of the development of high current cables, especially in DC, which are key for railways applications.

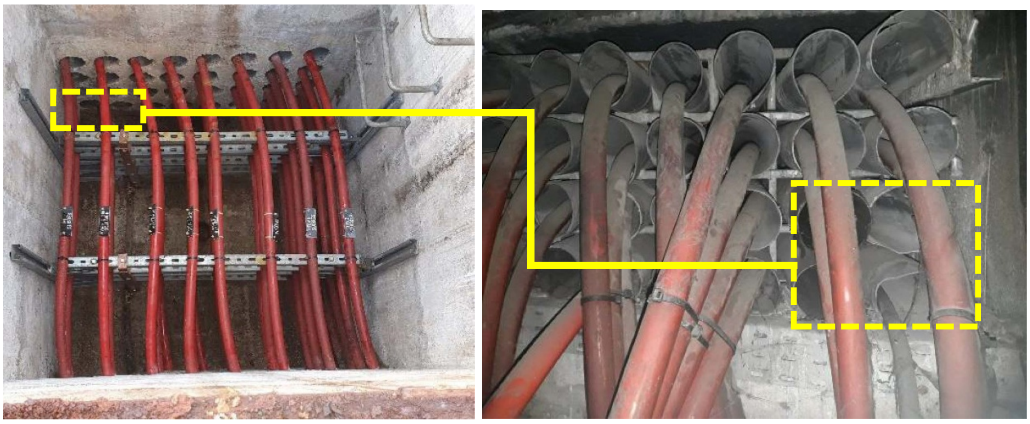


Figure 22. Saturated right of ways in railways infrastructure of big cities—example at the Montparnasse Station in Paris with only few pipes left for future power increase only possible with superconducting cables.

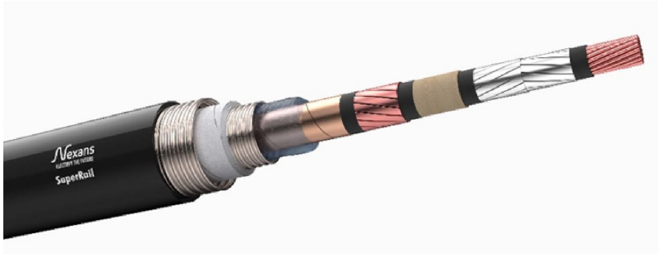


Figure 23. SuperRail 3.5 kA/1.5 kVDC superconducting cable (HTS) developed by Nexans for the French Railways (SNCF) to be pulled in existing 100 mm diameter pipe.

The dielectric properties in DC and cryogenic conditions [120] are deeply studied to insure reliability of future low voltage, medium voltage and high voltage applications for networks and for any application using power electronics. The seek for compactness in DC network for railways will benefit from progress in materials and modeling.

Most of the losses of DC superconducting systems in dense urban areas are coming from the terminations as superconducting links are usually rather short. To reduce the overall losses of the system one can move a part of the conversion chain at cryogenic temperature which foster the research of power electronic and power conversion at cryogenic temperature with interesting potential in term of compaction of equipment at equal or higher power [121]. All the works in progress for developing liquid hydrogen technologies have also a strong synergy with the superconducting technology [122]. The switch from liquid nitrogen to liquid hydrogen as a coolant can increase the superconducting cable AmpaCity by up to ten times offering an hybrid approach to store and transport energy (liquid hydrogen) and to transmit bulk electric power (superconducting cable).

Concluding remarks

The application of superconducting cables in DC railways is opening a new market for superconductivity as the conventional resistive cables do not allow to increase sufficiently transmitted power in the existing rights of ways of dense urban areas. This technology can not only solve local supply problem but secures also the full railway infrastructure network and provides tools to address the challenge of the train traffic increase and to reduce carbon footprint in very constraint urban areas. The cables superconducting technology is ready to transport current of several tens of kA and can be improved even further by reducing thermal losses of the system, especially in the terminations, with a potential in the future to take advantage of the presence of cryogen to revolutionize the conversion chain though power electronics at low temperature. The ongoing development of the use of liquid hydrogen for reducing world-wide carbon footprint in combination with renewable energy could also open a new chapter to ease the superconducting cable deployment and its performance enhancement.

Acknowledgments

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12. Commercialization of superconducting cables in Korea

C H Ryu[1], *J Y Lee*[2] *and J W Cho*[3]

[1] LS Cable & System Ltd, Republic of Korea
[2] KEPCO KEPRI (Korea Electric Power Research Institute), Republic of Korea
[3] KERI (Korea Electrotechnology Research Institute), Republic of Korea

Status

In the past two decades, various types of superconducting cable system have deployed in actual grid in several countries in order to meet more feasible and resilient power grid management and to provide a solution for paradigm shift in conventional grid by applying their advantages: bulk transmission capability due to lower transmission loss with lower voltage, no electromagnetic field emission and no thermal degradation. For this reason, more differentiated transmission has been serviced comparing with conventional power cables.

In order to meet more feasible and resilient power grid management, superconducting cables have been developed and been put in actual power grid in Korea to demonstrate their advantages. In this regard, various nominal voltage from medium to high voltage of AC and DC cables have been initiated their implementation in order to materialize more efficient power transmission [123]. Based on these remarkable achievements to lead the industry of superconducting cables, in 2019, Korea was announced by IEA (International Energy Agency) as the first country in the world to deploy a commercial superconducting cable which is to interlink two substations named 'Shingal Project' [124].

For commercial application, an innovative 'Shingal Project' has been launched in 2016 to deploy 1 km long AC 23 kV 50 MVA 3-core type superconducting cable system for substituting conventional AC 154 kV transformer as well as AC 154 kV cable between two substations. Then its initial operation reported by International Agency as the world first commercial service has been commenced in July 2019 [6].

Moreover, the second commercial project named 'Munsan Project' has been launch in 2022 to deploy 2 circuits of each 1 km long AC 23 kV 60 MVA 3-phase concentric superconducting cable system fully type tested respecting IEC 63075 for the first in the world in 2021. In this project, an innovative approach to commercialize 'Superconducting Platform' by use of superconducting cables for replacing conventional substation to distribute electric power to customers in urban area. Also, it is our expectation that excessive economic benefits could be approved when such innovative attempt is realized for its commercial operation.

The main purpose of advanced superconducting cable could be described as below:

- Existing or new high voltage substation could be replaced by such new compact system without using transformers.
- Power grid could be simplified by reducing number of substations by adopting our new system and superconducting hub station respectively.

Current and future challenges

Shingal Project: The world first commercial project

A. Project Feasibility

In order to draw additional electricity to densely residential area, medium voltage bus bar at Heungdeok substation was linked to Shingal substation via 1 km long AC 23 kV, 50 MVA superconducting cable system specified in table 5 instead of building new AC 154 kV substation along with same voltage cable as a conventional power grid scheme. By this state-of-the-art approach, KEPCO (Korea Electric Power Corporation) has been able to save total expenditure including the construction cost and operation cost and to avoid the public reluctance against power system built nearby.

'Shingal Project' has been launched its commercial service since July 2019 and then embarked a first chapter for commercial applicability of superconducting cable system to power grid by proving its cost-effectiveness. By analyzing CAPEX and OPEX via NPV (Net Present Value, the difference between the present value of cash inflows and the present value of cash outflows over a specific period), superconducting cable solution has highlighted its cost benefit as 9%-p comparing with conventional 154 kV XLPE cable solution.

Table 5. Specification of AC superconducting cable system of ‘Shingal project’. Reproduced from [124]. © IOP Publishing Ltd. All rights reserved.

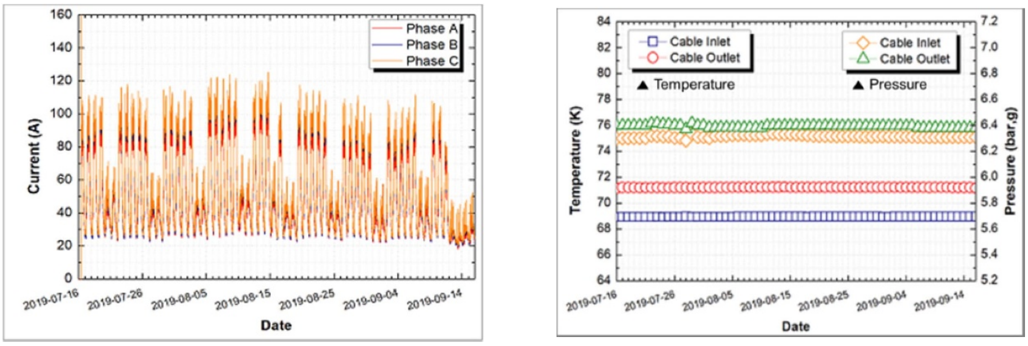
Item	Unit	Specification
Nominal voltage, rated current	kV_{rms}/kA_{rms}	23/1.26
Transmission capacity	MVA	50
Fault current	$kA\ s^{-1}$	25/0.5
HTS power cable type	—	3-core configuration
Type of superconductor	—	ReBCO & BSCCO
Circuit length	m	1,056
Cooling power	kW	7.5 kW@69 K
Operation Condition	K, bar.g	66–77 K, under 10 bar.g
Mass flow rate of LN_2	$kg\ s^{-1}$	0.4–0.6

Table 6. Transmission loss and the related cost.

		XLPE AC 23 kV 325SQ, 5-cct			HTS AC 23 kV 50 MVA, 1-cct		
Cable		AC loss	Power consumption	Subtotal	AC loss	Power consumption[a]	Subtotal
Transmission loss (kW)		90	—	90	2.5	44	46.5
Loss cost[b] [USD]	1 year	73 300	—	73 300	2,000	35 600	37 600
	30 years	2199 000	—	2199 000	27 000	1068 000	1128 000

[a] Power consumption: consumed by cryo-cooler and ancillary equipment.

[b] Applied LCOE: USD92.85/MWh, ref.: http://new.kpx.or.kr (December, 2022).



(a) Load current

(b) Operating temperature & Pressure

Figure 24. Operation data from Reproduced from [6]. © IOP Publishing Ltd. All rights reserved.

B. Grid benefit

One of the most efficient benefit on superconducting cable systems is less transmission loss than conventional XLPE cables as described in table 6 and it leads that its operation cost is also saved compared with XLPE’s even though power consumption by cryo-cooler for operating superconducting cables are considered in the operation cost.

C. Operation status

After, the system has been put into commercial operation until these days with load current up to $300A_{rms}$ as well as with operating temperature and pressure as shown in figure 24.

Advances in science and technology to meet challenges

Munsan Project: Demonstration of Superconducting station

A. Project feasibility

In order to reduce the product cost of AC 23 kV 3-core HTS cable, the development of AC 23 kV 3-phase concentric superconducting cable system has been completed consecutively in 2022.

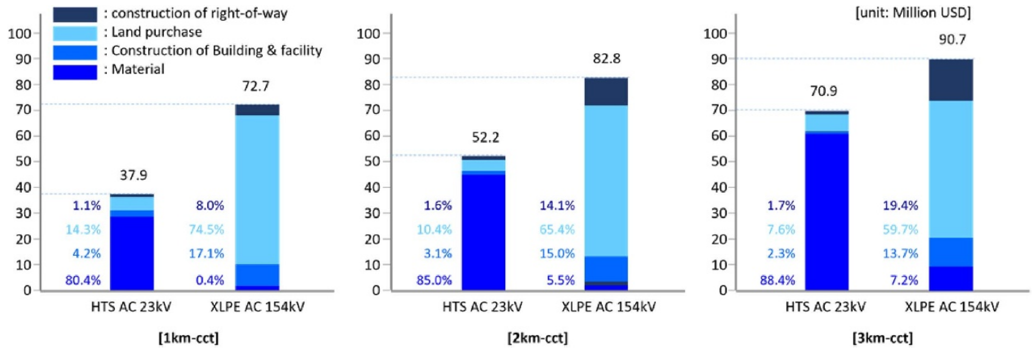


Figure 25. Comparative analysis on the economic feasibility between two solutions.

From the cost benefit viewpoint, a comparative analysis between above two solutions has also been done on the 'Project cost' depending on circuit length via NPV and the results are described in figure 25. Two remarks could be made:

1. Cost benefit at least 22%-p even the narrowest difference at 3 km-cct from saving the main cost by alternating AC 154 kV substation to AC 23 kV superconducting station
2. Reduction of right-of-way for two XLPE AC 154 kV cables to 1-one HTS AC 23 kV cable

In addition, the comparison indicates the cost benefit from superconducting cable is reduced inversely proportional to circuit lengths. It means that even the cost for land purchase of 154 kV substation is extremely higher than 23 kV superconducting station, the increment of variable material cost of superconducting cable dependent to the circuit length is getting close to the fixed cost of land purchase of 154 kV substation.

For its more intensive commercial practice in actual grid, 'Munsan Project' has been launched in 2022 for deploying AC 23 kV 60 MVA 3-phase concentric superconducting cable system between two AC 154 kV substations named 'Munsan' and 'Sunyu'.

B. Grid benefit

Furthermore, new conceptual substation so called 'Superconducting station' for only Switching & Load supply by eliminating transformers will be installed for demonstration in order to verify its commercial applicability instead of conventional AC 154 kV substations, alternatively.

Superconducting station will supply electric power by connecting medium voltage bus line of AC 154 kV substations nearby through AC 23 kV superconducting cables. In particular, since this system has only 10% of dimension of the conventional substation, it is expected to provide the solution to replace gradually AC 154 kV substation in urban.

Concluding remarks

KEPCO has successfully realized the commercial service of superconducting cable system for the first in the world. These innovative projects have proved that the cost-effectiveness has been proven in comparison with the conventional and superconducting grid schemes.

Furthermore, superconducting grid composed of superconducting cables and superconducting stations is able to reduce construction cost by simplifying grid components and is also able to reduce O&M cost by minimizing transmission loss comparing with conventional grid with its unique benefit. Particularly, superconducting station is expected to be a novel solution to deliver bulk power to hyper-scale Internet Data Center in Korea within next decade.

The advantages of our future demanded projects could be summarized as below:

Existing or new high voltage substation could be replaced by such new compact system without deploying transformers.

New scheme could provide two solutions of power grid simplification:

- To adopt 'superconducting hub station' for reducing the number of substations.
- To utilize superconducting cables for avoiding conventional multi cable circuits.

13. Status of HTS cable development in China

Xihua Zong[1] *and Bangzhu Wang*[2]

[1] Shanghai International Superconductor Technology Co., Ltd (SISC), Shanghai, People's Republic of China
[2] School of Electrical Engineering, Beijing Jiaotong University (BJTU), Beijing, People's Republic of China

Status

The year 2021 marked a critical year for the development of HTS cables in China: official projects of kilometer-scale cable demonstrations started operating in two megacities, namely Shanghai and Shenzhen. The central business districts of both cities have been suffering from high power load densities and difficulties to find space to lay down conventional cables for capacity increase. HTS cable technology, with its high transmission capacity and low space occupancy, offers an important solution to tackle the power transmission challenge in congested city areas [125, 126].

Ping'an Finance Centre is a landmark building in Shenzhen and the tallest construction in the Guangdong–Hong Kong–Macao Greater Bay Area. The Shenzhen HTS cable project was adding to the transmission capacity required to power the Ping'an Finance Centre, and was the first time in the world that HTS cables have been integrated into the power grid of a high-load urban center where the load density is more than 40 MW km^{-2}. It features a three-phase concentric cable design, 10 kV voltage, 2.5 kA current capacity, a length of 0.4 km, and an outer diameter of φ175 mm. All REBCO superconducting tapes were supplied by Shanghai Superconductor Technology Co., Ltd., detailed characteristics of which can be found in table 7. The cable has no intermediate joints, and is installed with a horizontal compact terminal. The HTS cable was manufactured using in house-developed automated cable-forming lines and continuous laser welding production lines for cryogenic pipes of superconducting cables. On 28 September 2021, the HTS cable was successfully connected to the grid; in February 2023, a high-load operation test was carried out. This project marks the first three-phase concentric superconducting cable in China. It has utilized superconducting cables to achieve the capacity expansion without engineering modification to a substation, saving the substation's footprint by 500 square meters and approximately 10 million Yuan in engineering investment. At the same time, it significantly reduces the level of engineering complexity for construction [126].

The Shanghai HTS cable demonstration project is located in Xuhui District. The 1.2 km-long cable connects two 220 kV substations, and has provided continuous, safe, and stable power supply to 49 000 users in the Xujiahui Business District and Shanghai Stadium area since 22 December 2021. With an annual power transmission of 180 million kWh, it saves 70% of underground pipeline space. The project has achieved maximum operating current of 2160.12 A, which is an operating load of 133.6 MVA, over a period of summer peak temperature of 41 °C, achieving continuous full-load operation. The detailed characteristics of the REBCO material used are listed in table 7. The cable structure adopts a Triad configuration with an outer diameter of φ185 mm, a rated voltage of 35 kV, and a rated current of 2.2 kA. It has also been designed with a fault current tolerance of 25 kA/3 s. The laying method involved the installation of cable ducts along the entire route, with two sets of intermediate joints and two sets of outdoor terminals.

Current challenges and solutions

Both HTS cables were destined to be handed over to the grids for operation: Shanghai HTS cable to be operated by the State Grid and Shenzhen HTS cable by the Southern Grid. To make sure the cables can satisfy operational requirements of the power grids, the two projects each commissioned 30 m of prototype cable for pilot testing. For example, the Shanghai project constructed two pieces of 15 m long superconducting cables, one set of intermediate joints, two sets of superconducting terminals, refrigeration systems, and monitoring systems. It successfully passed the validation of type test, as shown below in table 8:

Besides linking to the grids electrically, the HTS cables also have to physically conform to the limited space available on the congested grids. The Shenzhen Cable connects the 220 kV Binhe substation and the 110 kV Xinghe substation, there is a 24.2 m vertical drop between the two substations. The laying path has to include more than 10 bends of less than 90° and short-span S-shaped turns and go ups and downs around the existing transmission routes [127]. On the other hand, the Shanghai cable team

Table 7. Characteristic properties of REBCO tapes used in the two Chinese superconducting cable projects.

	Shenzhen cable	Shanghai cable
Material used	Cu-laminated REBCO tape	Cu-laminated REBCO tape
I_c specification (A, 77 K s.f.)	120	140 and 100
Width (mm)	4.8	4.8
Thickness (μm)	0.38	0.4
Total length volume (km)	80	300

Table 8. Details and results of validation tests performed on Shanghai HTS cable.

Test Item	Description	Results
Load cycle	20 cycles, 42 kV 2.2 kA(8 h/16 h)	Pass
Partial discharge	(under 1.73U0)	No charge (sensitivity 3.8Pc)
Dielectric loss, Tan δ	(21 kV)	1.8×10^{-3}(A Phase) 1.4×10^{-3}(B Phase) 1.1×10^{-3}(C Phase)
Lightning test	200 kV positive 10 times Negative 10 times	Pass
Voltage test	53 kV, 30 min	Pass
Pressure test	1.3 MPa 10 min	Pass

proposed a design for multijoint superconducting cables in narrow channels, and successfully constructed a kilometer-scale superconducting cable line with full-length pipe-laying (pipe diameter of 300 mm), solving the challenge of laying superconducting cables in confined spaces. They proposed segmentation of current leads with variable cross-section and invented adaptive intermediate joints. After introducing liquid nitrogen and cables effectively contracting upon cooling, the adaptive characteristic of intermediate joints would act to connect the contracted cables. The joint engineering effectively solved the challenge of topology of complexed channels and cable contractions upon cooling.

Maintaining operating temperature is crucial for the operation of HTS cable. This challenge is practically tackled by deploying advanced thermal insulation technology for the cable and a robust cryogenics design. As a first of this kind demonstrations in China, the two projects adopted different refrigeration systems. The Shenzhen project operates in a single-end refrigeration mode and installed Gifford–McMahon type refrigerators of cooling capacity of 7 kW at 70 K, operating in parallel at the Binhe substation. In order to improve the reliability of its cryogenic refrigeration system, online pluggable cold heads are realized. Some details of the Shenzhen Cable project are clearly illustrated in figure 26. The Shanghai project, as depicted in figure 27, took the opportunity to assess different types of refrigerators, it installed inverse Brayton refrigerators, Stirling refrigerators, and vacuum decompression refrigerator as a backup option. The cooling capacity of a single refrigerator can reach more than 12 kW at 69 K. Each refrigerator can operate independently, and altogether the 3 refrigerators assure a high operation reliability.

Future advances in science and technology to address more challenges

Moving forward, the Shanghai and Shenzhen project teams will focus their effort differently to address various types of challenges. The Shenzhen cable team plans to closely monitor the performance of the existing cable. Firstly, they will carry out long-term reliability assessment on the high-voltage bushings that operate over a wide temperature range. Terminal bushings operate at low temperature and over a steep temperature gradient; due to high humidity on site, the external insulation is often exposed to heavy condensation. These factors combined lead to significant deviations in the evaluation of parameters such as insulation resistance and capacitance when conventional standards are applied. It is a challenge to determine the values of parameters for bushing performance evaluation and reliability assessment under such conditions. To tackle the challenge, a research project has been established to simulate the operating conditions of the bushings and conduct accelerated aging tests to evaluate long-term reliability. Secondly, although the Shenzhen cable was successfully laid by overcoming the more than 20 m vertical drop, the cable may still be impacted by asymmetric movement induced by gravity and thermal cycling. In order to evaluate such risk, a research project is being conducted to establish a test platform

Figure 26. Landmark pictures of Shenzhen superconducting cable demonstration project. (a) Automated production line for concentric HTS cable cores. (b) Continuous welding and encapsulation production line for HTS cable core and cryogenic pipes. (c) Installed HTS cable in the cable tray. (d) Installed HTS cable in the cable trench. (e) Cryogenic refrigeration system. (f) HTS terminal in Binhe Substation.

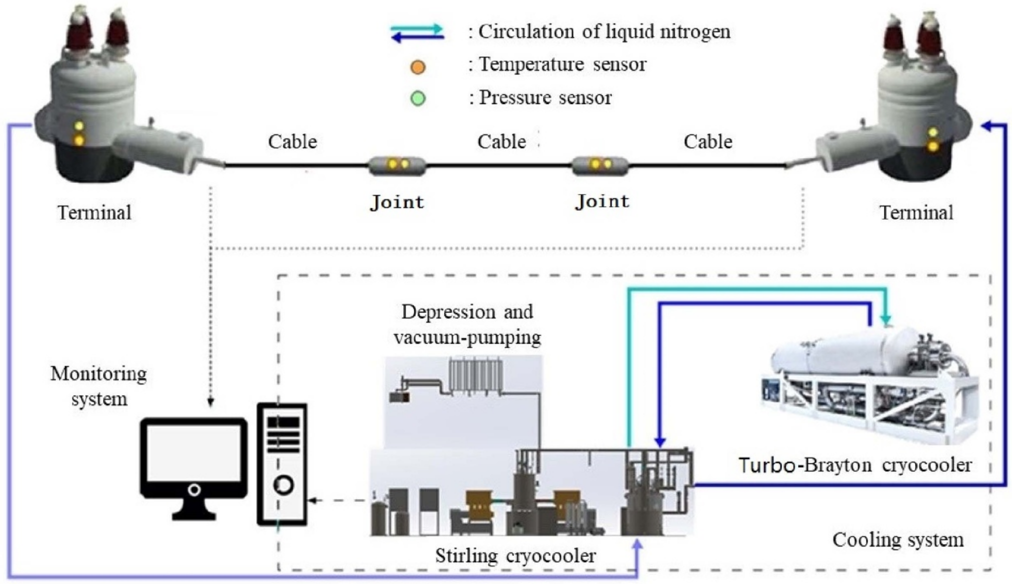


Figure 27. Schematics of the Shanghai 1.2 km long high-temperature superconducting cable and its auxiliary refrigeration and monitoring system.

for superconducting cable thermal expansion and contraction to quantitatively study the impact of gravity, bending, and other factors due to thermal variations.

Meanwhile, the Shanghai project team has been gearing up to push the cable technology to a larger-scale project. Besides evaluating the 3 types of refrigerators on their actual performance in day-to-day superconducting cable operation, it has been working to improve the overall efficiency of large-capacity refrigerators around 77 K. To cope with multiple km-scale of future cable distance, the Shanghai team is also actively developing superconducting relay joints. The most significant research is dedicated to develop online inspection and fault repair technique on the HTS cable cryostat, such that maintenance can be carried out without disruption to the grid operation.

Concluding remarks

In the past 5 years, the high temperature superconductivity industry in China has developed rapidly. With the successful completion of HTS cables in Shanghai and Shenzhen in 2021, and their continuous operation on grids ever since, it has fully demonstrated that HTS cables can be deployed on grids to tackle power transmission challenges in congested city areas in China. Through development efforts by the Shanghai and Shenzhen cable project teams, all associated technologies, including but not limited to raw material processing, insulation, terminal fabrication, refrigeration, long-length cable and joint fabrication, have been well proven in performance. For the two projects, Shanghai Superconductor Technology Co., Ltd. supplied nearly 300 km of copper-laminated REBCO tapes, the material demonstrated robust engineering properties and reliability in operation. With upcoming production scale-up and significant cost reduction outlook of the REBCO material, and further maturity of related engineering technologies, HTS cables will gradually enter commercialization in China and are expected to become a solution for extending the ultra-high voltage transmission networks to urban city centers.

14. Operational experience of AmpaCity superconducting cable system

Kai Allweins

Nexans Deutschland GmbH, Germany

Status

Compared to conventional cable solutions superconducting cables have the capability of carrying higher currents in conjunction with typically lower electrical losses which makes superconducting cables particularly interesting for applications where these points are in demand, e.g. high power transmission. Many projects have been successfully realized or demonstrated in the past years—remember the projects and applications in the main chapters before. The technology is getting closer and closer to commercialization, but market penetration is not yet satisfactory. Apart from the technological advantages of superconducting cables, the operational experience is still a key factor in achieving greater acceptance among grid operators and finally acceptance in terms of expansion and refurbishing of grids, thus further advances must be made on this topic.

This section focuses on the German AmpaCity project [128] successfully operated in the Essen city grid and reports on a wide range of measurement data and experience which have been gathered during 7 years (2014–2021) of grid operation. AmpaCity is typical for many superconducting cable projects that have been realized before and after.

In the end, the operational experience of a superconducting cable system stands and falls with the reliability of the cooling system. Operational experience is therefore in many cases a cooling system operational experience. A downtime in cooling system operation usually leads in a downtime of cable operation, if no additional precautions are taken. Thus, attention must be paid during the cooling system design to keep downtime to an absolute minimum. The next two main chapters—open and closed cooling systems—will further describe both cooling systems concepts.

Current and future challenges

In the AmpaCity project [128] a 10 kV, 2300 A (40 MVA) superconducting AC cable system including a fault current limiter and cooled by a highly reliable open cooling system [110] was operated, connecting two substations in the Essen city grid along a distance of around 1 km. The commissioning of the cable system was done in December 2013, the connecting to the grid in March 2014, afterward normal operation commenced. During operation, all measurements were recorded by a data acquisition system.

Figure 28 illustrates a recorded power profile of the AmpaCity AC cable system. The profile is typical for an inner-city operation with a higher load on five weekdays and a lower load at weekends. It also reveals seasonal deviations, here Christmas and the turn of the year. The cable was operated under this power profile for practically the entire operating time. The corresponding total losses of the cable result in 1820 W ± 70 W, slightly fluctuating with ambient temperature.

Figure 29 illustrates a typical year of temperature and pressure history of the liquid nitrogen supply and return to and from the cable system. The inlet temperature was regulated to 68.0 ± 0.1 K with an associated mass flow of 450 ± 20 g s^{-1}. The outlet temperature was around 70 K ± 0.1 K, increasing by 0.3 K in the summer month due to higher ambient temperatures. Inlet and outlet pressure were 9.0 ± 0.1 bara and 6.3 ± 0.2 bara, respectively.

Figure 29 shows isolated inlet temperature peaks (dT: -0.6 to $+0.8$ K), which can be identified as planned switch of redundant liquid nitrogen circulation pumps during operation. Also, visible is a temporary lowering in pressure (dP: -1.3 to -0.5 bar), which is related to refilling of the liquid nitrogen storage tank of the open cooling system.

This long-term measurements give a good insight into the behavior of the complete cable system. On a long timescale, e.g. uncommon additional thermal losses of the cable system can be recognized by monitoring nitrogen temperatures and mass flow over months. On a shorter timescale, e.g. unusual fluctuations in nitrogen mass flow over days or weeks might be identified as a source of an upcoming problem with a nitrogen circulating pump.

The challenge is to bring and use this information into the control system—without any user interaction—to increase the operational performance and therefore the user experience.

Advances in science and technology to meet challenges

From the beginning, the AmpaCity system operated exactly as designed, including fault current limitation. Short-circuit tests up to 3-phase 4.5 kA were carried out during operation, proving that this

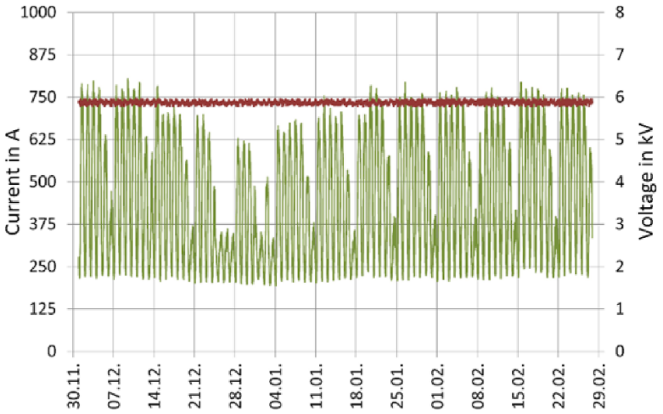


Figure 28. Power profile during three month AmpaCity operation.

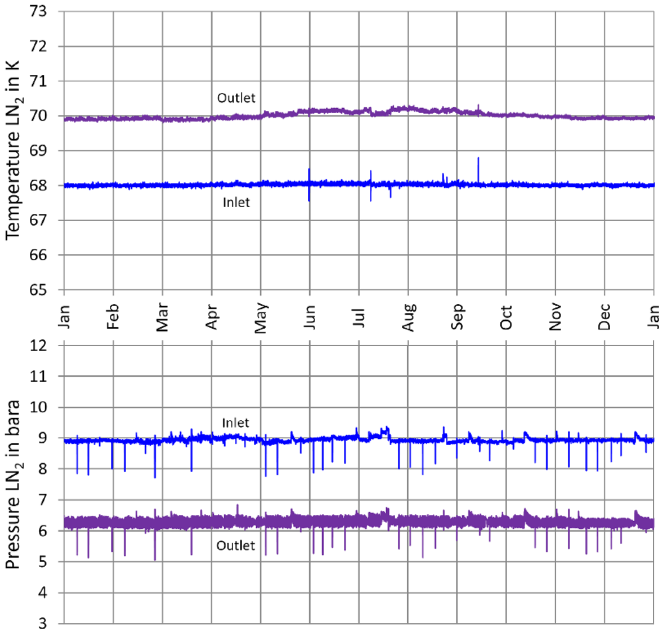


Figure 29. Temperature and pressure history of the nitrogen supply during 1 year AmpaCity operation.

relevant operating situations outside a test field were mastered, too. The system was in operation without problems over 7 years.

Further improvements of both cooling and control systems were done during operation. As an example, a modification of the cooling system vacuum pumps after freezing of humidity and optimizations like a smooth switching between the redundant liquid nitrogen circulation pumps with a temperature settling <0.8 K. The control system optimizations led as another example to an improved response time after automatic reclosing for continuous operation after HV faults.

All operational experience to improve the cooling and control system behavior and performance was important especially in the beginning of the project, but required human attention. Consequently, this process was automized. One important automatization were so-called ‘predictive warning’—a general long-term analysis of the measurement data, done by the control system itself, which enables an additional level of operational support in the project.

To give an example where ‘predictive warning’ helps in system operation: Assuming a slow but constant increase of the nitrogen temperature in the inlet termination, the cable will stay a long time in normal operation before any alarm is given to the grid operator, since the inlet temperature is the lowest temperature of the cable system. Looking at the second termination the situation is different. Collecting thermal and electrical losses of the cable system, the temperature is higher here, closer to the alarm threshold, but it will see an increase of nitrogen temperature only time-delayed related to the amount of nitrogen mass flow over the 1 km length of the cable.

An extract of this kind of information from the measurement data is feasible and will give a pre-warning to the cooling system operator to identify and fix early any potential problem and as a further stage of automatism to let the cooling system itself identify and fix in the range of cooling system operational conditions. Avoiding a potential downtime of the system, the grid operator will only be informed afterward if necessary, but not disturbed during normal operation of the cable system. In summary, the AmpaCity system was working very stable, so only a few 'predictive warnings' were recorded, typically when a maintenance interval had been scheduled anyway.

Concluding remarks

Initially it was planned a demonstration period in the AmpaCity project of at least 2 years, finally the superconducting cable system was 7 years in operation. In the years AmpaCity was one of these 'lighthouse projects' and the success of this project contributed to the development and realization of future superconducting cable systems. It can be assumed that the project would have never been extended over years without sufficient operational experience and therefore acceptance among the grid operator.

Certainly the system design was one of the main safeguards of this success, but as set out in this chapter, the overall operational experience can be improved comparatively easy by increasing the level of measurement data processing and further automatism. Despite all efforts to further optimize superconducting systems technically, such aspects should never be neglected.

Acknowledgments

The author would like to thank all partners who contributed to the AmpaCity project as well as the German Federal Ministry of Economics and Technology supporting the project.

15. Open cooling systems

Friedhelm Herzog

Messer SE & Co. KGaA, Germany

Status

Cooling of cryostats for superconducting power cables is typically carried out using subcooled liquid nitrogen. The main components of a corresponding cooling circuit are circulation pumps, volume compensation vessels and subcoolers. In 'closed' systems, cold for the subcoolers is provided by cooling machines. In 'open' systems, cold is generated in a comparatively simple heat exchanger using nitrogen evaporating under vacuum conditions. Liquid nitrogen is provided via low temperature storage tanks, which, with appropriate piping, can also be used as volume compensation vessels.

The heat ingress through the thermal insulation of the cable cryostat is normally the most important design factor of the cooling system. Additionally, magnetic field losses of the superconductor and the heat input through the current leads must be considered. This provides a first indication of the liquid nitrogen mass flow that is required to keep the maximum temperature in the cable below the desired target value.

The mass flow cannot be increased arbitrarily because otherwise the pressure drop would be too high and the hydraulic friction of the liquid nitrogen in the cable cryostat becomes another relevant heat source. If the permissible limits are reached, intermediate cooling stations are required.

The sum of the aforementioned heat impacts is the 'net' cooling capacity required for the superconductor cable. If you add the dissipation of the circulation pumps and the heat input through the thermal insulation of the cooling unit, you get the 'gross' cooling capacity that has to be provided by the subcooler.

The 'AmpaCity' cable from the grid operator Westnetz in Essen went into operation with an open cooling system back in 2013. The most important data for what was then the world's longest superconductor cable are listed below:

• Length:	1000 m
• Voltage (AC):	10 kV
• Power:	40 MVA
• Net cooling capacity:	1.8 kW@64 K
• Gross cooling capacity:	3.4 kW@64 K

The 3.4 kW gross cooling capacity during regular operation requires 68 kg h^{-1} of liquid nitrogen. Using vacuum pumps, a pressure of 150 $\text{mbar}_{(\text{abs.})}$ is generated for nitrogen evaporation at 64 K (close above its melting temperature). This allows the circulating liquid nitrogen to be recooled to 67 K.

The cooling and pumping system itself causes a heat ingress of 47%. This quite high proportion is due to the fact that standard products were used as circulation pumps. By further developing the pump design, it is possible to almost half their heat input.

Current and future challenges

When commissioning the superconductor cable, there are additional requirements that the cooling system must meet. The cable cryostat is commissioned in the following steps:

- Purging (drying) with warm gaseous nitrogen
- Cooling by controlled temperature reduction of the purging nitrogen down to 77 K
- Flooding the cable cryostat with liquid nitrogen
- Subcooling of cable cryostat and its liquid nitrogen content down to 67 K

To purge the cryostat, nitrogen is withdrawn from the storage tank, converted into the gaseous state with air-heated evaporators and then warmed up to approx. 320 K using an electric heater. The cold gaseous nitrogen required for the cooling phase is created by mixing liquid and vaporized nitrogen, and the cryostat is flooded directly via the bottom connection of the storage vessel.

The most difficult process is subcooling the liquid nitrogen in the cable cryostat. To do this, the circulation pump must be switched on. Since the nitrogen is at its boiling point in this phase, care must be taken to ensure that the pumps do not cavitate during starting. This can be done, for example, by installing another subcooling device at the liquid nitrogen inlet of the pumps in addition to the subcooler on their pressure side.

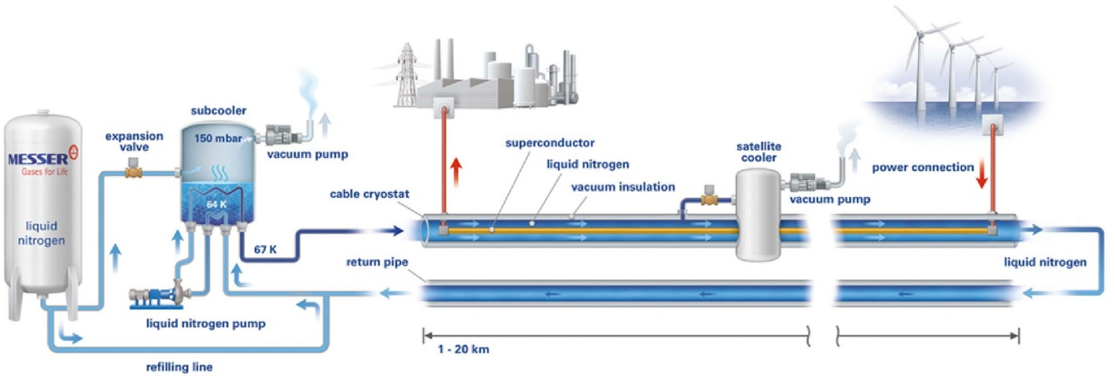


Figure 30. Cooling and pumping unit for a cable cryostat with an intermediate subcooler.

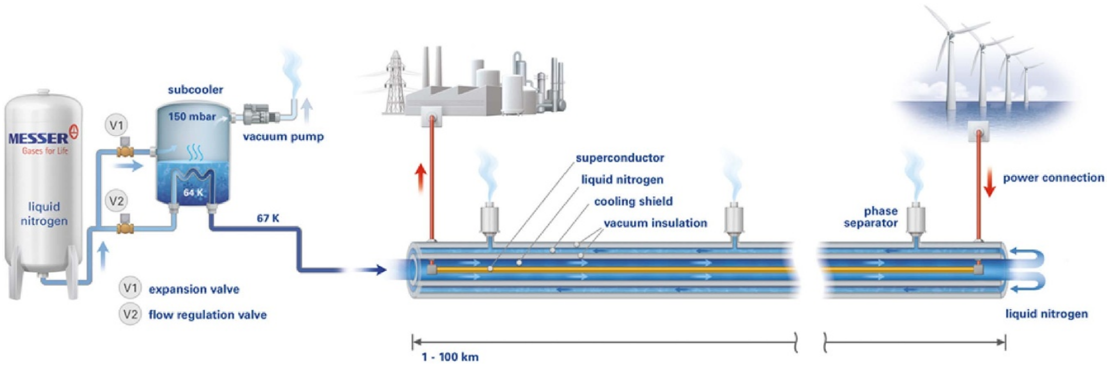


Figure 31. Cooling unit for a cable cryostat with active cooling shield.

A good solution for this task is a double-subcooler. Here, the circulating liquid nitrogen first flows through heat exchanger tubes (or plates) at the pump inlet, then through the circulation pump and then through heat exchanger tubes at the pump outlet. All heat exchange surfaces are installed in one apparatus in which the cooling nitrogen evaporates under vacuum conditions. The cooling on the suction side of the pumps prevents cavitation, while their dissipation is compensated on the pressure side. The cooling capacity to remove the other heat ingresses can be distributed between both heat exchangers.

During the subcooling phase, in addition to the cooling requirements for regular operation, there is a further cooling demand to cool down the cable cryostat from 77 K (temperature after flooding) to 67 K (operating temperature). To ensure here a fast procedure, the subcooler must have an appropriate power reserve. In open cooling systems, this causes no additional investment costs when the reserve vacuum pump, which is typically installed for redundancy reasons, is used during the subcooling phase.

Advances in science and technology to meet challenges

For longer cable routes, intermediate cooling stations are required. In open cooling systems, these 'satellites' can be installed very easily. The satellites simply consist of a subcooler with the associated vacuum pumps (figure 30).

A satellite requires no cooling water and little electrical power. A nitrogen storage vessel is also not necessary, as a small amount of liquid nitrogen is diverted from the circulation to cool it. This amount is then fed back into the circulation line directly from the storage tank at the base cooling station.

Cable cryostats with intermediate cooling stations allow routes up to approx. 20 km. At longer distances these cooling concepts prove to be difficult because of the required mass flow of circulating nitrogen and the then exponentially increasing pressure drop. Therefore, not only additional subcoolers are required, but also intermediate pumping stations. This introduces additional heat into the circulation and the cooling systems become increasingly complex.

Therefore, for longer cable routes, continuous cooling of the cable cryostat using an active cooling shield is recommended. This makes the cryostat design more complex, but cooling becomes much easier, especially because no circulation pumps are required (figure 31).

The cryostat then consists of an ‘outer’ cryostat, the cooling shield, and an ‘inner’ cryostat in which the superconductors are located. The temperature difference between the inner and outer cryostat is below 20 K. With a conventional cable cryostat, a temperature difference in the range of 200 K can be expected. This means that the heat ingress into the superconductor is about a factor of 10 smaller with the cooling shield design. Therefore, the required liquid nitrogen mass flow is also smaller by a factor of 10, which results in the pressure drop decreasing by a factor of 100.

The liquid nitrogen mass flow in the inner cryostat corresponds quite well with the need for nitrogen to be evaporated in the cooling shield. Therefore, the nitrogen emerging from the inner cryostat can be fed directly into the cooling shield and returned in countercurrent towards the base station. To prevent too high pressure in the shield, the nitrogen evaporated here is blown off along the cable route using appropriate degassers (phase separators). In this way, cable routes in the 100 km range can be implemented.

Concluding remarks

Cooling superconducting cables with liquid nitrogen (‘open’ cooling) is technically easy to implement. The reliability of such a cooling system was clearly demonstrated by 7 years of continuous operation of the AmpaCity cable in Essen. The investment costs are comparatively low because no cooling machines are required. This is particularly noticeable, when for reliability reasons cooling machines have to be carried out redundantly.

With open cooling systems, there is automatically redundancy for the cold because the systems can be supplied from more than one nitrogen source (air separation plant).

Closed cooling systems have an advantage if their electricity costs are significantly lower than the corresponding costs for liquid nitrogen. Nevertheless, even with closed systems, many of the hardware components of liquid nitrogen cooling systems are required, as these are needed for start-up and commissioning. Optimal solutions often arise from hybrid systems in which a cooling machine provides the required cooling capacity during regular operation, and nitrogen cooling is available for start-up, peak loads or malfunctions and maintenance cases. Corresponding concepts make it possible to save on the reserve cooling machine, that is often required for redundancy reasons, and its operating costs when it runs in standby mode.

16. Closed cooling systems based on Stirling cryogenerators

Francesco Dioguardi

Stirling Cryogenics B.V., The Netherlands

Introduction

Since the first prototype HTS systems have been build, Stirling Cryogenics has been involved in many HTS projects to provide the required cooling power in the 20–50 K as well as 60–150 K temperature range. These cooling systems are based on the Stirling Cycle Cryogenerator producing cooling power by internal compression and expansion of helium gas [129]. This cooling power becomes available in a heat-exchanger, optimized to either liquefy a gas stream or to cool a gas or liquid flow. This makes the Stirling Cryogenerator a versatile machine to cool a flow without the need of compressing and/or expanding such flow itself.

Stirling cryogenic cooling systems based on these Cryogenerator can hence make use of a cold helium gas flow at 20–30 K for DC cables, supplying 50 W to over 2 kW; forced flow and subcooled liquid nitrogen LN2 at 67–75 K for AC cables, supplying 500 W to over 10 kW; as well as other fluids like liquid Neon or boiling nitrogen for motors, generators and fault current limiters. Stirling Cryogenics has been designing and manufacturing Cryogenerators and customized cryogenic systems for various applications for 70 years.

Cooling of DC cables

By the lack of AC losses, DC cables generate less power per length, as there will be only cryostat losses. With less heat load, this gives the opportunity to work at a temperature level of 20–30 K, meaning less HTS conductor is required. Cooling fluid of choice is cold gaseous helium. This is flown through the cable internal piping by a cryogenic fan (Stirling CryoFan). Over the length of the cable the temperature will rise by heat losses and energy is removed again by flowing the Helium gas through the Cryogenerator heatexchanger (figure 32).

Start point for the design of such system is the maximum allowed cable temperature at the exit side of the gas flow, as a higher temperature is obviously not permitted.

In the Stirling Cryogenerator the gas is cooled with a certain temperature difference $\mathrm{d}T$, choice of which is important and influenced by various factors that also influence each other. For example, a small $\mathrm{d}T$ is advantageous as this raises the temperature of the cooler, raising the cooling capacity.

However, smaller $\mathrm{d}T$ also means a larger required mass-flow and therefor volume flow of the helium. Which in turn will cause more friction losses, requiring more labor to push the gas through the cable. This has to be provided by the CryoFan that hence will introduce more heat.

The optimal balance has to be found, to increase available cooling power as much as possible without destroying this at the same time by friction.

A very important part in this calculation is the flow resistance of the cable as function of flow.

The lower this is, the more efficient the cryogenic system can become. This may mean that, especially for longer lengths, standard corrugated line will cause too high pressure difference $\mathrm{d}P$ and a better suited and smoother, but special types of inner piping may be required.

An optimum end-result can only be obtained by an iterative discussion and calculations between the manufacturers of the tape, cryostat and cooling system. All will need to cooperate and each may (and will) be forced to work at a suboptimal point for their own system part, however as a result create the most optimal total system.

Cooling of AC cables

AC HTS cables a have much higher power per length as there are not only heat losses by the cryostat, but also substantial AC losses generated by the cable itself. To cool these losses, a flow of liquid nitrogen is needed which is subcooled through-out the length of the cable assuring a one-phase liquid flow without gas bubbles. If any gas, with a much lower cooling ability, would appear this will lead to an immediate hot-spot and quench of the total cable length.

A suited cooling system shall create not only the flow by liquid nitrogen pumps, but also have a system that keeps this liquid in a subcooled state. This is done by a pressurizing vessel controlling the system pressure both up and down (figure 33).

The vessel shall have the possibility to raise pressure if this tends to go down, caused by the subcooled liquid trying to get to an equilibrium state. Also, it must be possible to lower the pressure in case

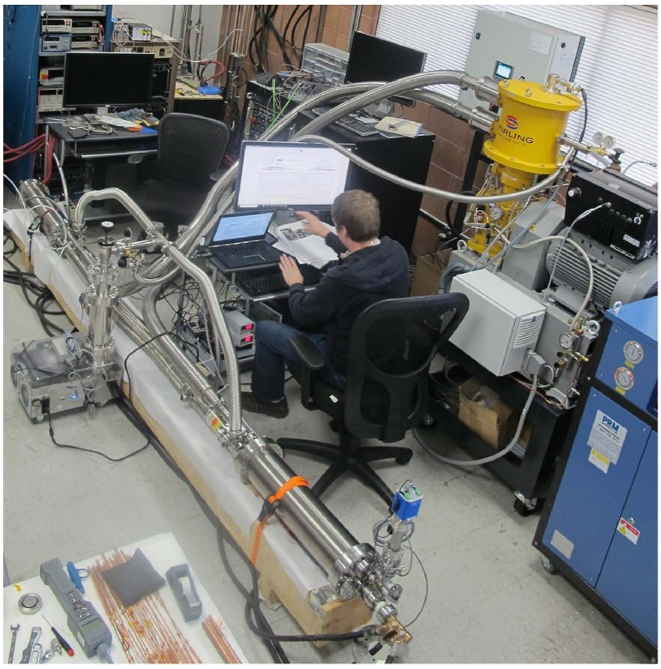


Figure 32. 20–30 K cooling loop set-up to cool DC cables. Courtesy of Advanced Conductor Technologies LLC, Boulder CO, USA

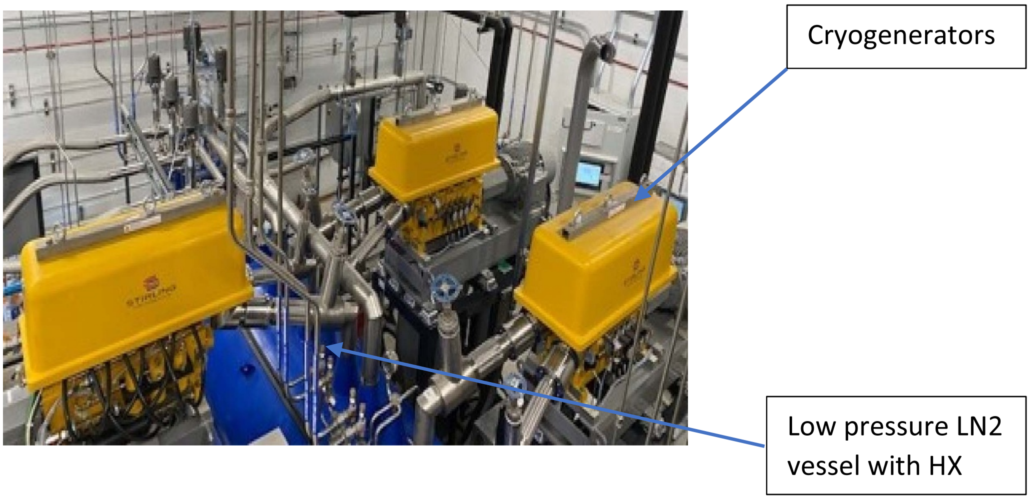


Figure 33. Stirling Cryogenics 67 K sub-cooled LN_2 cable cooling system.

of an event in the cable and system due to which the pressure tends to rise. The cooling power of the Cryogenerators can be transferred by pumping LN_2 directly through the cold heads, but more commonly this is done by re-liquefying LN_2 in an equilibrium state of 67 K and 243 mbar(a).

In this boiling liquid nitrogen reservoir, a heat-exchanger is submerged through which the pressurized liquid nitrogen of the cooling loop is pumped. In this way, this liquid will be subcooled to about 68 K after which it is pumped through the cable. Although the subcooled liquid state is the usual situation while the cable is in use, the system is also to be equipped with the possibility to cool down the cable and fill it as steps before subcooling is reached. This requires an ingenious set of valves to perform these different steps of cool-down and of course also warm-up and emptying of the cable.

Typically, these systems are build according an n+1 configuration, meaning that a redundant Cryogenerator and pump are integrated, starting up and taking over almost immediately if one of the functional components should get out of order.

Examples of such systems are the one installed in 2021 at Comed in Chicago for an AMSC project [130], and the one to be commissioned 2nd quarter 2024 for Supernode in Ireland.

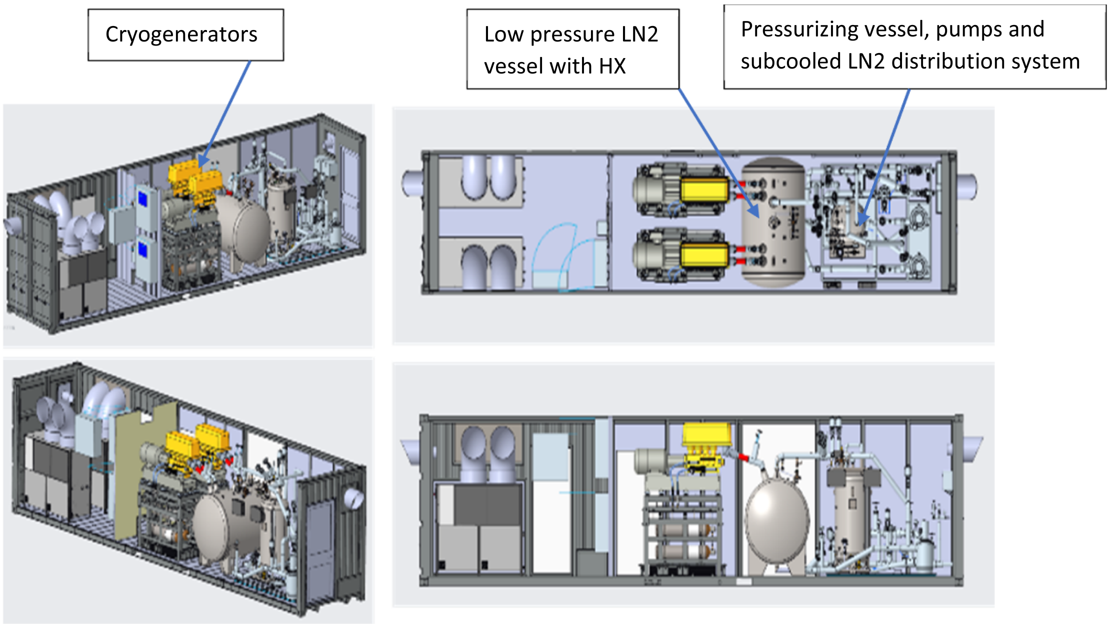


Figure 34. Stirling Cryogenics 67 K sub-cooled containerized LN_2 cable cooling system.

Future developments and challenges

With the relative short HTS cables build so far, pressure drop over the length and required cooling power are limited. In the near future however, cables will become longer and reach one to several kilometers. This is a challenge for the cryostat builders, as they will need to assure the pressure resistance per length gets lower. From inlet to outlet the same dT will need to be used, while the flow will need to increase with length, as well as resistance and pressure drop. If this is not addressed, pumps will need to be much larger to create a larger inlet pressure, also creating an increase in flow losses.

Next to reducing pressure drop, also another cooling system set-up could be thought of. For example, to have a cooling system at each side and so halve the dP for the pumps or create a cooling system at regular intervals wherever dT tends to go over 5 K.

Apart from these challenges at the cable side, more and more Cryogenerators will be required. Although this is in fact possible, it would be preferred not to need more than 10 units as vacuum jacketed piping connections will get more and more complex and the system will need more than 3 units of 40 ft containers to be installed (figure 34).

For this reason, Stirling Cryogenics has started a development Project in 2023 to create a Cryogenerator with 4–5 times higher capacity. This is not just a matter of making the piston surface 5 times larger. The Stirling Cycle is a complicated thermodynamic process in which all sizes and volumes need to be in a proper balance to assure the high efficiency of the current version will be matched.

Design and modeling of the cycle will be finished by the end of 2024, based on which mechanical production drawing will be made. During the first half of 2025 parts will be produced, and the first prototype will be assembled and tested. Based on these results, this bigger version of the Cryogenerator is planned to be on offer from 2026.

17. Superconducting energy pipeline for electricity and LNG transmission

Liye Xiao and Qingquan Qiu

Institute of Electrical Engineering, Chinese Academy of Sciences, People's Republic of China

Status

A superconducting energy pipeline consists of a HTS cable and a cryogenic pipeline in which the coolant is fuel such as liquid hydrogen (LH_2) and liquid natural gas (LNG), then it might be an effective transmission system for the transport of electricity and liquid fuels simultaneously. As the HTS cable is lossless for DC currents and has distinguished current-carrying capability, and the clean liquid fuels transportation system is very high in energy density and large transmission capacity, then the overall efficiency and economy would be improved by combining the two systems using the cryogenic fuel as the coolant of the superconducting cable and sharing the refrigeration system and the adiabatic pipe [131–135].

Since the liquid hydrogen temperature is 20 K, which is far below the critical temperature of HTSs, the superconducting energy pipeline for electric/LH_2 transmission has a natural advantage. However, due to the limited demands of hydrogen fuel, the economics of extremely low temperature refrigeration and the safety of LH_2, it is difficult to achieve large-scale application of electricity/LH_2 energy pipelines in the near future. With the rapid development of natural gas pipeline transportation, the research of superconducting energy pipeline for electricity and LNG transmission has gradually developed in recent years. Using LNG as the cooling medium, the Carnot efficiency of performance COP coefficient of the refrigerator cycle will be increased from about 0.3–0.36 (LN_2) to 0.43–0.50 (LNG), the energy consumption of the cooling system could be reduced.

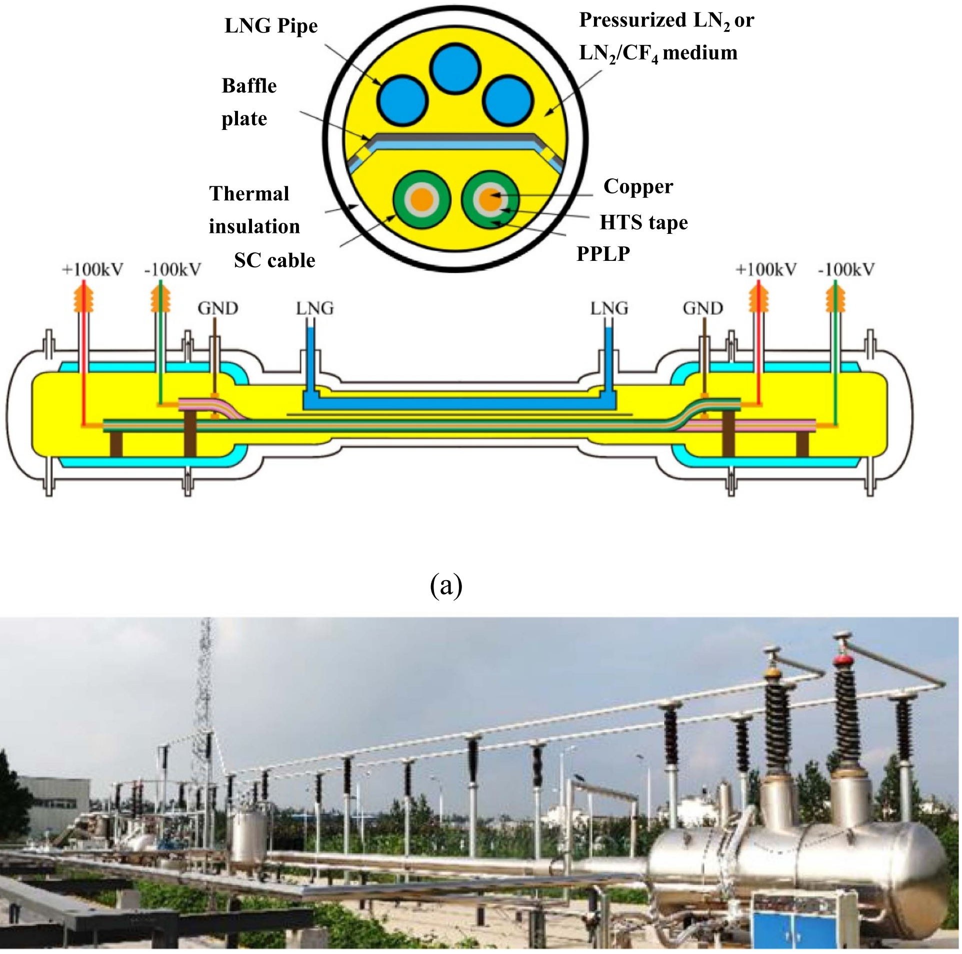
In 2012, a team at Xi'an Jiaotong University in China proposed a conceptual design scheme for long-distance transmission of LNG and DC superconducting cables, using LNG as the cooling medium of superconducting cables [136], the operating temperature zone is 110–120 K, and the superconducting cable is wound with Hg1223 material. In 2015, a team of Chubu University in Japan proposed a new type of structure for superconducting DC energy pipeline [137, 138]. The LNG pipeline is used as the cold screen for superconducting cable, and the superconducting cable is cooled by a separate LN_2 circulation system. The DC superconducting cables are usually used in the energy pipeline in order to reduce the AC losses and increase the transportation distance. In 2017, a new structure with LNG cooling and protected by pressurized LN_2 or LN_2/CF_4 mixture was proposed by a team of the Institute of Electrical Engineering (IEE), Chinese Academy of Sciences. It should be noted that the LN_2/CF_4 has a larger bubble point and electrical insulation strength than pure LN_2, but CF_4 might not be eco-friendly due to its high global warming potential. Fortunately, the storage and transportation technology of CF_4 gas is relatively mature, the CF_4 gas is not easy to volatilize after being mixed into liquid nitrogen. Based on this new structure, the development and test of a 10 m, 10 kV/1 kA superconducting DC energy pipeline prototype was completed in 2019 [139]. In 2021, the development and full-power operation test of the 30 m, ±100 kV/1 kA DC superconducting energy pipeline prototype was implemented in China [140, 141], as shown in figure 35.

Current and future challenges

Although superconducting energy pipelines have some advantages over other energy transportation system, it should make many efforts to achieve potential application. The challenges that are faced with the energy pipeline are as follows:

At first, for power /LNG energy pipelines, there is a lack of HTS materials suitable for the LNG temperature zone: the temperature of LNG is 110 K, but the critical temperature T_c of commercial Bi-based superconducting material is just 110 K and has not current-carrying capacity at this temperature. Although the critical temperatures of Tl-based and Hg-based superconductors are higher than 110 K, these superconductors contain heavy metals (toxic), and are hard to be fabricated into wires or tapes. The solution scheme for the problem as above is to use LNG pipeline as cold screen can, but it needs to adopt an independent liquid nitrogen (or hybrid coolant) circulation system, which increases the construction cost. If one cools the LNG down to 90–100 K, it would increase the operating cost of the system. Then, fabrication of superconducting materials with T_c higher than 110 K is of great significance to promote the large-scale application of energy pipelines.

Secondly, it should deal suitably with the interaction of electric power and fuel transmission under complex operating conditions and fault conditions, otherwise it would lead to disasters for the energy pipeline. Flow of LNG is often changed or even intermittent according to the requirements, while the



(a)

(b)

Figure 35. Structure diagram (a) and photos (b) of the 30 m ± 100 kV/1 kA DC superconducting energy pipeline. Reproduced with permission from [140].

power transmission operates in a more complex mode such current variation, short-time overload and even experiencing of short-circuit etc, therefore it is necessary to control the LNG flow and heat transfer of liquid insulating medium during the transmission of LNG and electric power. In addition, under fault conditions such as the short circuit in the grid and the insulation breakdown in the pipeline, it is still necessary to control the effects of fault evolution and ensure the safety of energy pipelines.

Thirdly, there is the need of developing technologies for long-distance energy pipelines. The fabrication and test of a short superconducting energy pipelines is much simple, while a long-distance superconducting energy pipeline needs to take the advantage of the relay joint design of superconducting cables and cryogenic pipelines, cold shrinkage compensation, refrigeration /pressurization station, and substation/converter station. In addition, there are a lot of engineering problems in the design and layout of superconducting energy pipeline when considering the complex geographical environment such as turning, crossing roads, mountains, valleys, and rivers, etc.

Finally, if the use of LNG may have to be reduced in the long term due to carbon emissions, the hybrid cooling system should be adapted to operate without LNG, which could be replaced by LN_2 cooling system conveniently. Moreover, the cold hydrogen gas could also be considered if the hydrogen is transported and used on a large scale in the future.

Advances in science and technology to meet challenges

In order to promote the development and large-scale application of superconducting energy pipelines, the following advances in science and technology should be further studied to meet the challenges:

(1) Research on new superconductors with T_c higher than LNG. In order to make full use of LNG as coolant and reduce the operating costs of HTS cable, the research and development of new superconductor operating in the LNG temperature or higher should be continued.
(2) According to suitable application scenarios, it should be improved the comprehensive benefits of superconducting energy pipeline. Considering that many wind power plants, LNG receiving/storage stations and large gas-fired power plants are being built, it is necessary to transport electricity and LNG to the load-center at the same time, creating conditions for the implementation of long-distance superconducting energy pipelines.
(3) Further improvement of the economy and safety of superconducting energy pipeline is needed. The principal structure of superconducting energy pipeline should be designed to avoid the occurrence of chemical explosion in the case of extreme failure of superconducting cable. Furthermore, considering the practical application scenarios, the system design scheme and operation process of superconducting energy pipeline should be optimized to improve the economy of comprehensive energy transmission.

Concluding remarks

With the revolution of carbon-neutrality, the primary energy would be dominated by renewable energy, and the terminal energy would be dominated by electric power. This important change would lead challenges to the construction of the new energy and power system. Usually, the load centers are far away from the renewable energy centers and large amount of energy and power would be transported over long distance, then many kinds of new energy technologies including superconducting energy pipeline would have potential applications in the future energy and electric power. Superconducting energy pipeline prototype with transportation of LNG and electric power has been developed, and some science & technology advances should be taken before it would be used in the future.

Acknowledgments

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18. Combined liquid hydrogen and electricity pipeline

Tabea Arndt, Sebastian Palacios, Mira Wehr
and Michael J Wolf

Karlsruhe Institute of Technology, ITEP, Germany

Status

A future sustainable energy system will be based on electricity and—to a still unknown extent—on hydrogen and its derivatives as molecular energy carriers. The transport sector, in particular large vehicles, is benefitting in particular from using liquid hydrogen (LH_2) as a fuel. So, there is definitely a need ('pull factor') from mobility or bulk users of hydrogen. The continuing electrification of mobility, industry and households increases the demand in electric energy, too. As the transport directions of electric energy and hydrogen may be the same for a number of cases, a combined transportation offers synergies and advantages—especially when the electric part is based on HTS[31]. In the past there have been already studies and attempts to combine superconductors and LH_2 [142–144], however, the LH_2 was mainly used as a cryogen (in a corrugated pipe architecture) and not for bulk transport of hydrogen, and the superconductor was chosen from either LTS or MgB_2. To reduce the flow-resistance, to increase the transportation distance and to save area consumption of cables and pipelines, a hybrid liquid hydrogen and electricity pipeline (short HEP) may be the means of choice. Figure 36 shows the general, minimum scheme of such a pipeline. Using HTS for the electric part may offer increased electric power capacity at lower voltage overcoming the present limitation of conventional HVDC cables while the transport of LH_2 eliminates the need for dedicated cooling equipment. Furthermore, the use of HTS increases the potential operational margins of the HEP compared to LTS or MgB_2 (e.g. critical temperature of REBCO vs operational temperature $T_{\mathrm{op}} \approx 22$ K). For a higher operational margin in temperature under transport current, a higher amount of HTS will be required due to the moderately reduced critical currents (increasing the cost share of wire in the HEP) but will be technically feasible even under high-pressure liquid hydrogen and temperatures higher than 30 K. For MgB_2-due to the vicinity to $T_c \approx 39\,\mathrm{K}$, the reduction of the critical current is much more severe.

Initial design parameters for a HEP of transfer capacity of 200 MW electric and 200 MW molecular power are given in table 9, a general arrangement is shown in figure 36. The most important difference in the design approach for HEP compared to other cryogenically cooled transfer lines stems from the requirement to not only safely cool the HTS, but to transport a bulk amount of molecules/cryogenic liquid. Thus, the diameter of the HEP is mostly determined by the mass flow requirements and not minimized to the cooling demand of the electrical conductors. The 'molecular power' is simply given by multiplying the mass flow by the gravimetric energy density of hydrogen (33.3 $\mathrm{kWh\ kg^{-1}}$; net heating value). Critical current calculations show that the HTS REBCO tape demand of the prototype of the two co-axial single-layer tape arrangements (figure 36) can be as low as 13 tapes of 3 mm-width per layer due to the high critical current I_c of REBCO at the operating temperature (per tape: $I_c\,(T = 30\ \mathrm{K}) \approx 1000\ \mathrm{A}$).

For the technology demonstrator of $\approx 20\,\mathrm{m}$ length, the hydrogen mass flow rate will be reduced to few grams per second and the test will be carried out at low voltage; however, the design of the HTS cable is derived from the requirements from the application case.

Current and future challenges

Presently, there is a lack of practical demonstrators; the maximum length reported so far for a corrugated tube power transmission line is 30 m [144]. The work presented in [143, 144] pointed out that a prospective power transfer of several tens of MW (by electricity and hydrogen, each) can be realized in the flexible cable under study. However, electrical current and high voltage was only demonstrated separately.

The technical challenges for a HEP to be addressed are the initial pressure (limited by available cryogenic pumps) and the pressure drop as well as the temperature increase along the length—details on the latter may be found in [74]. Choosing a smooth pipe instead of a corrugated tube facilitates long distance HEPs considerably due to lower friction factors and flow resistance.

To keep the input of environmental heat at acceptable levels, the thermal insulation has to be chosen carefully. Except for some niche applications, due to an operational temperature substantially lower

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[31] Presently, a techno-economic case study on a practical use case in the North of Germany is conducted, but details will be published elsewhere in the course of 2025.

Table 9. Design parameters for a potential target application of a HEP.

Quantity	Symbol	First target application	Unit
Length of HEP	L	10	km
Nominal electric power	$P_{\mathrm{n,\,electr.}}$	0.2	GW
Nominal voltage	U_{n}	± 10	kV
Nominal current	I_{n}	10	kA
Design temperature	T_{des}	30	K
Lay angle	α	Still open	°
Inlet pressure	$p_{\mathrm{LH2,in}}$	0.3	MPa
Outlet pressure	$p_{\mathrm{LH2,out}}$	$\geqslant 0.2$	MPa
Inlet temperature		21	K
Max. temperature	T_0		K
Mass flow	$\dot{m}_{LH2}$	1.67	Kg s^{-1}
Nominal 'molecular power'	$P_{\mathrm{n,LH2}}$	0.2	GW
Current usage	$I_{\mathrm{n}}/I_{\mathrm{c}}$	0.85	n.a.
Maximum electric field in insulation	E_{lim}	14.2	kV mm^{-1}

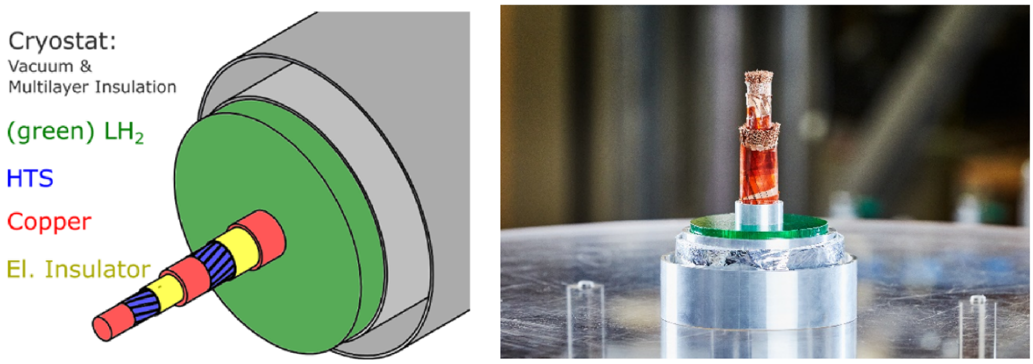

Figure 36. General scheme of a combined liquid hydrogen and electricity pipeline (left), mock-up of a demonstrator HEP (right).

than the boiling temperature of nitrogen and oxygen, a double-wall cryostat with vacuum and multilayer insulation seems inevitable. Two main arguments underline the importance of a double wall cryostat. First, the thermal heat leaking into the cryostat has to be minimized (the use of a pipe instead of a corrugated tube minimizes the flow resistance) to maintain a sub-cooled fluid over long distances. The thermal conductivity of microsphere insulations at atmospheric pressures shows a minimum heat conductivity of ≈ 0.05 W (m K)$^{-1}$, whereas for a vacuum/superinsulation < 0.00016 W (m K)$^{-1}$ can be reached [145]—therefore a reduction of the heat flow by more than a factor of 300. Second, the vacuum space not only serves as a thermal insulation, but also as a control and safety measure for LH$_2$ leaks of the inner tube. However, this ensures that the outer surface of the HEP has the same temperature as the environment and that the thermal impact on the environment is negligible.

The HTS and the LH$_2$ should be thermally coupled well, but at the same time they have to be separated electrically—in particular in the case of failures and short currents.

The hydrogen puts additional requirements on the used materials (e.g. to avoid embrittlement). Special care has to be assigned to the seals used in the system. Hydrogen is of high diffusivity and commonly used seals made of PTFE or polyimide may have to be replaced by metallic seals.

The terminations of a HEP are more complex than for state-of-the-art liquid-nitrogen cooled HTS power transmission lines as they combine partially contrary requirements on thermal and pressure gradients, high voltage insulation, current transfer, electrical contacts, mechanical stability and bulk flow of hydrogen at the same time. Furthermore, the final destinations of electrical energy and hydrogen use might differ (e.g. larger transport distance of LH$_2$ than electric energy).

The challenge to introduce a HEP as completely new type of device into either electric power grids (at the appropriate power level) and into the gas grids simultaneously by adopting the corresponding

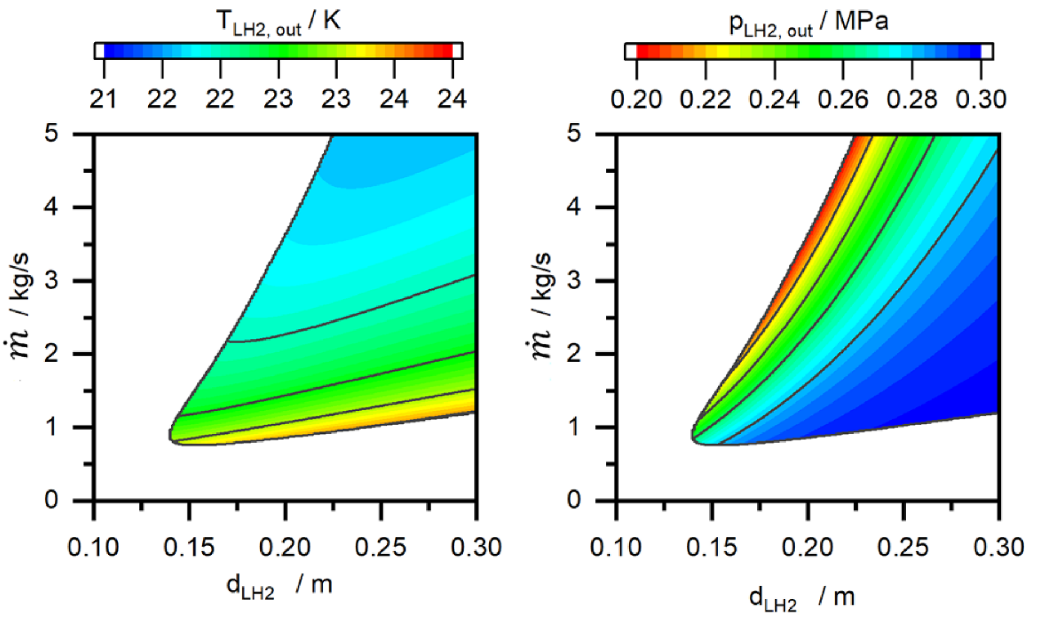

Figure 37. Outlet-temperature (left) and -pressure (right) of a HEP and the dependence on mass flow $\dot{m}$ and LH_2 pipeline diameter d_{LH2} (by project AppLHy!).

rules and regulations might be underestimated easily. The public acceptance of a HEP on public ground (on-ground or underground) is certainly a topic which has to be addressed in width and depth.

A starting ground may be created by elaborating on the safety aspects (faults and shorts, HazOp, operational limits, control and metering etc). In the HEP, LH_2 is used as a coolant and an energy vector enclosed in a vacuum. Therefore, the appropriate strategy for vacuum segmentation, control and loss and -even more important- measures to avoid the freezing of oxygen at cold parts have to be implemented.

Furthermore, potential industrial partners have to be identified and included into scientific and technical work as early as possible to get the liquid hydrogen technology out of rocket science.

Advances in science and technology to meet challenges

The results reported in [143] created a base for further work. In 2021, within the German National Hydrogen Strategy, the flagship project TransHyDE [146] was started. The collaborative research consortium AppLHy! is focusing on transport and use of liquid hydrogen and includes also research and development towards a HEP based on HTS CCs. First reports are published [147], others to come. In 2022, the EU-funded project SCARLET was initiated [148] aiming for a flexible LH_2-cooled power transmission line using MgB_2-wires for the hybrid energy transportation.

In general, cryogenic cooled superconducting cables are known for many decades and there is a manifold of globally spread installations to demonstrate feasibility and benefits (see other chapters of this publication). However, using LH_2 instead of LHe or LN_2 is limited to [143, 144].

When addressing long-distance transport of bulk LH_2 in rigid pipelines, the designs have to consider the different envelopes, support structures and thermohydraulic relations as well as the risk of using a reactive instead of an inert cryogen. The thermohydraulics are still following the physics laid out in e.g. [74]. Initial estimations on the pressure loss and temperature increase of a HEP treating LH_2 as incompressible fluid are shown in figure 37. The initial design parameters have been chosen to inlet-pressure $p_{\mathrm{in}} = 0.3\,\mathrm{MPa}$, inlet-temperature $T_{\mathrm{in}} = 21\,\mathrm{K}$ and a transport distance of $L = 10\,\mathrm{km}$ and pressure loss of not more than 0.1 MPa.

Today, cryogenic ‘commodity pumps’ are available up to pressures of ≈ 0.6 MPa. In general, it would be beneficial to operate at higher pressures, however, the critical pressure of hydrogen of $\approx$ 1.3 MPa will put additional challenges to the thermohydraulic description due to the proximity of the critical point.

The electric design of the superconducting cable may follow the state-of-the-art design rules of superconducting cables—except that the lower operating temperature in a HEP leads to an increase of critical current density in the HTS tapes compared to LN_2 temperatures and may allow higher operating currents but will require consequently an increased cross section of normal conductor to cover faults.

Concluding remarks

The use of HTS and LH_2 in a HEP might enable unrivalled transport options for green energy as electric energy and molecular energy in one compact component. This offers advantages related to space consumption and way of right, too.

Presently, a thorough techno-economic assessment of the viability of a HEP for selected use cases is still missing but ongoing.

However, the general tools for design, simulation and operation are generally available. The demonstrators to be built in ongoing (AppLHy! And SCARLET) and future projects are required as proofs of principle and to reach the next level of maturity.

Acknowledgments

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List of abbreviations (section 18)

Abbreviation	**Explanation**
AppLHy!	Collaborative Research Project in the Hydrogen Flagship Project TransHyDE, Germany
HazOp	Hazard and operability study
HEP	Hybrid energy pipeline
HTS	High-temperature superconducting tape
LH_2	Liquid hydrogen
LTS	Low-temperature superconductor
MgB_2	Magnesium-diboride superconducting wire
PTFE	Polytetrafluorethylen (Teflon)
REBCO	Rare-earth barium copper oxide: an HTS with the 123-structure
SCARLET	An European project on a HEP—see section 19

19. MgB_2 power link with liquid hydrogen

Christian-Eric Bruzek[1] *and Adela Marian*[2]

[1] ASG Superconductors, Italy
[2] RIFS Potsdam, Germany

Status

Superconducting power cables based on magnesium diboride (MgB_2) have been demonstrated at the gigawatt level [149], proving the technological maturity and reliability of the MgB_2 manufacturing processes. In addition to its low cost, high-yield wire manufacturing and easy cabling, MgB_2 is ideally suited to operate at liquid hydrogen (LH_2) temperature. The combination of superconducting cables and hydrogen in the same pipeline opens the door to simultaneously transmitting two energy vectors electricity and hydrogen, so-called hybrid or dual transmission. This idea was initially proposed in 2004 [150] and a proof of concept was given in 2013 [143]. With hydrogen becoming key to reaching decarbonization goals worldwide, its efficient distribution is also gaining a lot of attention [151]. A hybrid distribution system has cost-saving potential, as the infrastructure costs for electricity and hydrogen can be shared. Moreover, the LH_2 coolant generates revenues when delivered to customers, thus reimbursing the costs of the cryogenic system.

Relevant applications for a hybrid distribution system are green transportation systems and energy-intensive metallurgical industries, where high amounts of both electrical and chemical energy are required. Some examples are schematically shown in figure 38. For instance, in a green port application, the hydrogen and electricity requirements for one ship are 200–300 m^3 (2–3 t h^{-1}) LH_2 aboard and 50–100 MW of electrical power, respectively.

Against this background, the European project SCARLET [122] has a work package dedicated to demonstrating a 500 MW superconducting cable system for hybrid energy distribution at 25 kV and 20 kA with an LH_2 mass flow of 2–10 t h^{-1}. Based on MgB_2, the cable system takes advantage of the high current capability of the superconductor to operate at medium voltage, while still maintaining the gigawatt transmission level. The goal is to bring this system to type testing, which is essential for obtaining the acceptance of the end users. This will be followed by 6 months of operation in the field. All along, the safe operation in LH_2 will be prioritized and efforts will be made to advance the standardization framework.

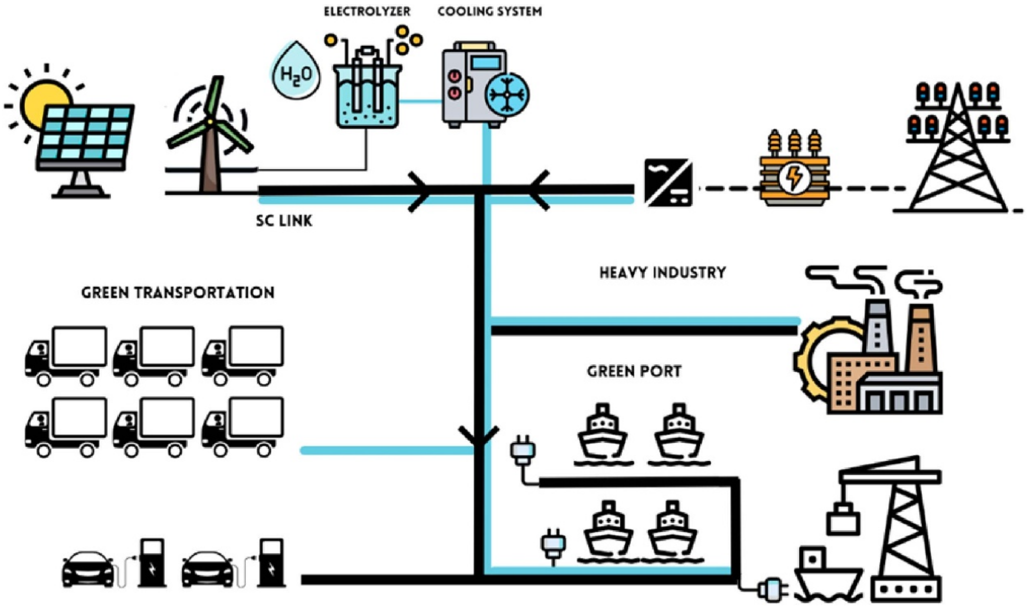

Figure 38. Main applications for the combined transport of electricity and hydrogen: energy-intensive industry along with ground and maritime transportation.

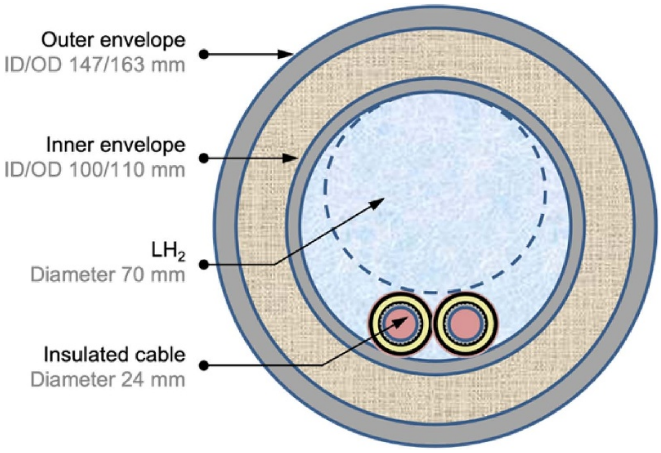

Figure 39. Cross section of a hybrid energy system consisting of 2 × 500 MW MgB_2 cables and LH_2 distribution with a mass flow of 2 t h^{-1}, which is one of the business cases considered in SCARLET. © [2024] IEEE. Reprinted, with permission, from [155].

Current and future challenges

As mentioned above, MgB_2 wires can already be industrially manufactured in kilometric piece lengths [152]. Likewise, cryostats and cryogenic envelopes are commercially available [153] and can maintain LH_2 at up to 20 bar pressure over long lengths. They have been used for decades in aerospace applications and can be considered as a mature technology.

Current challenges associated with a hydrogen-cooled cable based on MgB_2 mainly concern the voltage insulation, cooling machines, and cable accessories, as briefly summarized below:

- Voltage insulation: As extruded polymers are too brittle at cryogenic temperature, the voltage insulation is made of lapped tapes. Beside its cryogenic role, the LH_2 also contributes to the dielectric insulation by filling the gaps in the structure of the lapping. To our knowledge only a very limited number of measurements on the dielectric properties of LH_2 are available, and they indicate that LH_2 is at the very least equivalent to liquid nitrogen.
- Cooling machines for LH_2: They are based on mature industrial solutions for liquid helium and liquid nitrogen. However, specific designs and operation procedures must be considered due to the flammability of hydrogen in its gaseous form. Note that oxygen is solid at the operating temperature of the cable (20 K) and the risk of miscibility with hydrogen and subsequent explosion is therefore very low at cryogenic temperature.
  Today large quantities of LH_2 (3 tons) can be produced from industrial liquefaction units and delivered by trucks, well suited for the foreseen applications. This is however too large compared to the 10–100 kg required for the cable testing. The lack of availability of LH_2 in small volume makes the qualification processes difficult.
- Cable accessories: These are cable joints and terminations, necessary for achieving long lengths and connecting to the grids. Comparable technologies to the ones used for HTS cables are envisioned. Also here, the operation and safety in LH_2 need to be validated. The accessories must follow safety rules set in the standards for flammable gas [154] and any risk of LH_2 leakage at the joints must be avoided. Additionally, the filling and un-filling procedures will be defined and carefully followed. An exhaust zone of the gaseous hydrogen flow into safety areas in case of emergency is required in the termination environment.

Lastly, a general issue with superconducting cables is the lack of electrical standards for testing, which are mandatory for the acceptance of this innovative technology.

Advances in science and technology to meet challenges

As illustrated in figure 39, a very compact cable transporting 2 × 500 MW can be manufactured based on the considerations presented above. Its compact design keeps a large section of the cryogenic envelope free, allowing for the distribution of a significant LH_2 mass flow as required by the applications envisioned for this system [155].

Even if today's performance of the MgB_2 wires is already sufficient for the hybrid energy cable, improving the critical current and reducing the AC losses can still be beneficial. The performance range of the MgB_2 material is largely underused, hence the potential for improvement is significant. For example, changing the microstructure of the MgB_2 material by doping precursor powders with carbon particles, and optimizing the heat treatments are currently under investigation. As a first result, an increase of more than 20% in critical current has been recently measured [156].

By contrast, assessing the dielectric performance of lapped insulation in LH_2 is mandatory. Unlike for many cryogenic fluids, the dielectric properties of LH_2 are not well characterized due to the lack of appropriate test facilities with cryogenic vessels adapted to LH_2. One such test facility is being built within the SCARLET project and will soon become operational.

To overcome the difficulty of purchasing small quantities of LH_2, smaller liquefaction units are necessary. These systems are supplied by standard bottles of gaseous hydrogen. Such small machines that can deliver up to 50 kg d^{-1} are in the final phase of development by Absolut System [157] and will be soon available for projects.

Concerning the safety in LH_2, thorough risk analysis must be applied, for example by using the hazard identification methodology. Within SCARLET, this procedure will be carried out for the first time to ensure the safe operation in a type test. The results are expected to help draw first recommendations for operating a hybrid energy cable system.

As no standards are yet available for superconducting cable testing in DC, the testing program will be based on the protocols developed for the Best Paths project [149] and the recent standard for AC superconducting power cables [158]. Overall, the SCARLET work will provide a sound basis for including DC superconducting cables in the standardization framework.

Concluding remarks

A full MgB_2-based hydrogen-cooled cable system including two terminations and a joint will be designed, industrially produced, and tested in the European project SCARLET. This will be the first full-size demonstrator for combined electricity and hydrogen transport, which meets the requirements for grid integration. Apart from characterizing and validating LH_2 as an insulating medium, the type test and long-term testing will be important steps toward the preparation of safety standards for operation in hydrogen and of recommendations for a superconducting medium-voltage DC test standard.

Acknowledgments

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Data availability statement

No new data were created or analysed in this study.

ORCID iDs

M Noe 0009-0006-5870-968X
T Puig 0000-0002-1873-0488
X Obradors 0000-0003-4592-7718
D C van der Laan 0000-0001-5889-3751
S Pamidi 0000-0002-5748-8938
R Bach 0009-0005-4704-1955
R Prinz 0009-0002-9368-2372
S Ishmael 0000-0002-0938-8393
C Räch 0009-0004-2665-4755
F Herzog 0009-0006-6373-2657
T Arndt 0000-0002-7797-8862
S Palacios 0000-0003-4145-6365
M Wehr 0009-0008-1747-0339
A Marian 0000-0002-9159-5227

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