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Superconducting high-current cables

Without resistance into the application

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Superconducting cables and wires are well developed and the first economic applications are foreseeable. One obstacle to widespread application is the still insufficient number of successful prototypes in long-term use. On top of that, there is a lack of knowledge about the many possible applications and the degree of maturity of the technology. In this article, we present the state of development for high-temperature superconductors, various possible applications and an exciting project in Munich.

The discovery of high-temperature superconductivity in 1986 by Karl Alexander Müller and Georg Bednorz [1] initially led to euphoria, especially with regard to its use in energy technology. More than 30 years later, it has to be concluded that only a few applications with high-temperature superconductors have been successfully developed commercially to date. Yet a large number of demonstrators and prototypes have confirmed the potential of these applications and impressively demonstrated their technical feasibility [2].

This is especially true for superconducting power cables and lines, where the world's first grid application with high-temperature superconductors took place in 2001 [3]: The US cable manufacturer Southwire installed a 30 m long test cable on the company's premises, which successfully supplied production facilities with electricity. Since then, more than ten superconducting power cables with lengths of up to one kilometre have been successfully tested in long-term network applications. The 1 km long 10 kV cable AmpaCity in the city centre of Essen, designed for 40 MVA, can undoubtedly be listed as the global benchmark for meeting operational requirements. It has been in successful use since spring 2014 [4].

Grid operators still have doubts regarding the reliability, cost-effectiveness and operational safety of superconducting cables, which is often due to a lack of knowledge about the state of development. Nevertheless, more and more projects are now starting a permanent network deployment, and first pilot lines already promise an economic use. This includes, among others, the SuperLink cable project started in 2020 by Stadtwerke München for the technological development of a compact 110 kV cable that could prospectively replace a 380 kV cable and thus avoid a costly tunnel construction in the centre of Munich.

Currently, there are increasing signs that superconducting power cables will be successfully established. An important driver is the existence of a complete supply chain, from superconductor material to long-term operational maintenance and monitoring. The superconductor material is now competitively available and can be supplied within a reasonable time for a cable project. The grid operation in Essen has shown that the maintenance still required on the cooling system can be carried out without interrupting operations.

We continue to be very confident about the future use of superconducting energy cables due to the new requirements of the energy transition and the growing importance of hydrogen. In the case of high-power transmission lines, approval and acceptance by the public are playing an increasingly important role. Here, superconducting cables offer decisive advantages, as they can transmit the highest power at lower voltages and without electromagnetic and thermal influence on the environment in very compact routes. This not only simplifies the approval process, but also leads to greater public acceptance.

Since liquid hydrogen at 20 K offers the highest energy density for storage, some transport and transmission tasks appear very attractive in this aggregate state - despite the additional energy required for liquefaction. Since the cold environment is then available for the superconductor, the combination of liquid hydrogen and high-temperature superconductivity is almost ideally suited for energy transport and transmission tasks as well.

Superconducting materials

Superconductors must be cooled below a critical temperature T_c in order to exhibit superconducting properties. High-temperature superconductors (HTS) are defined as a whole class

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of compounds that are characterised by their T_c being above 25 K. Before the discovery of HTS, all known superconductors had critical temperatures below this, so that today they are also called low-temperature superconductors.

Today, many HTS compounds are known, each of which can be divided into three groups. The most prominent group, discovered by Müller and Bednorz in 1986, is based on copper oxide compounds (cuprates). Their most important representatives for technical applications are $YBa_2Cu_3O_{7-\delta}$ (YBCO) with a T_c of 92 K, $GdBa_2Cu_3O_{7-\delta}$ with 93 K and $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO) with 110 K. In 2001, it was discovered that the metallic compound magnesium diboride, MgB_2, with a T_c of 39 K falls within the range of high-temperature superconductivity. And only a few years later, Japanese scientists were able to demonstrate superconductivity with a transition temperature of 26 K in the material $LaFeAsO_{0,9}F_{0,1}$ [5]. Many other compounds of these iron and arsenic-based superconductors with transition temperatures of up to 56 K have since been discovered [6].

However, copper oxide superconductors with a T_c above 77 K are of particular interest for cable applications in power engineering, as liquid nitrogen can then be used as a cost-effective cooling medium suitable for cooling long cables. All of these cuprates are complex ceramic compounds, the production of which is costly for various reasons. On the one hand, the chemical composition of the compounds has to be controlled within very narrow limits - and that at process temperatures of 700 °C and more. Secondly, a high superconducting current-carrying capacity of this class of materials is only given if the compound does not have any major disturbances of the crystal structure. Since even grain boundaries represent such a disturbance, the production of long wires in particular is a challenge. Ideally, they must represent a single crystal hundreds of metres long. The alternative is a sufficiently good, continuous biaxial, i.e. biaxial texture of the substrate to achieve a high crystal quality of the superconductor layer grown on it. In addition, sufficient flexibility is also necessary so that these wires can be used in applications. This is also a challenge, considering that these are brittle ceramic compounds.

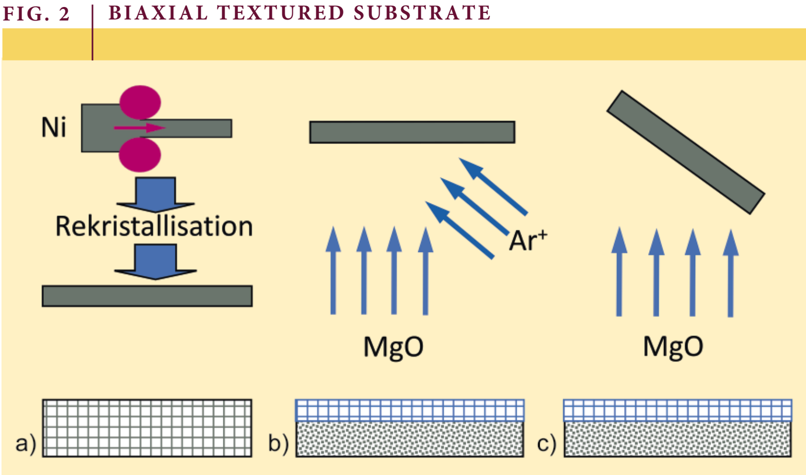
Since the discovery of HTS, research and development has taken up this challenge. Various processes are now available with which it is possible to produce industrially long wires with excellent superconducting properties (Figure 1). The metallurgical powder-in-tube (PIT) process was the first to be developed. In this process, BSCCO is filled into silver tubes, which are then rolled into thin, filamentated tapes. However, since these first-generation HTS tape conductors consist to a large extent of silver, the material costs are fundamentally high.

Fig. 1 Production facilities for manufacturing HTS tape conductors at THEVA Dünnschichttechnik GmbH in Ismaning near Munich.

Second-generation tape conductors are an alternative with significantly lower material costs. These consist of a thin metal foil as a flexible substrate and a very thin layer of the superconductor. In order to achieve the necessary crystal quality of the superconductor, different processes have been developed (Figure 2). All of them are based on the fact that a crystalline oriented substrate is produced first, the orientation of which is then taken over by the HTS layer through epitaxy.

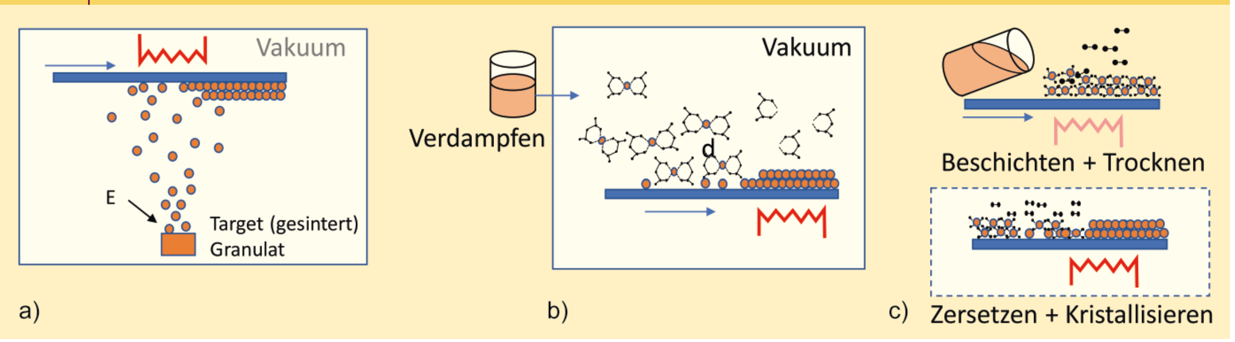
While in the so-called RABiTS process (Rolling-Assisted Biaxially-Textured Substrate) the substrate itself is already textured by rolling and recrystallisation, in the other two processes, IBAD (Ion Beam Assisted Deposition) and ISD (Inclined Substrate Deposition),

FIG. 2 | BIAXIAL TEXTURED SUBSTRATE



Three methods: RABiTS (Rolling-Assisted Biaxially-Textured Substrate, a), IBAD (Ion Beam Assisted Deposition, b) and ISD (Inclined Substrate Deposition, c) for the fabrication of biaxially textured substrates for long HTS tape conductors [7].

FIG. 3 | Superconductor layer

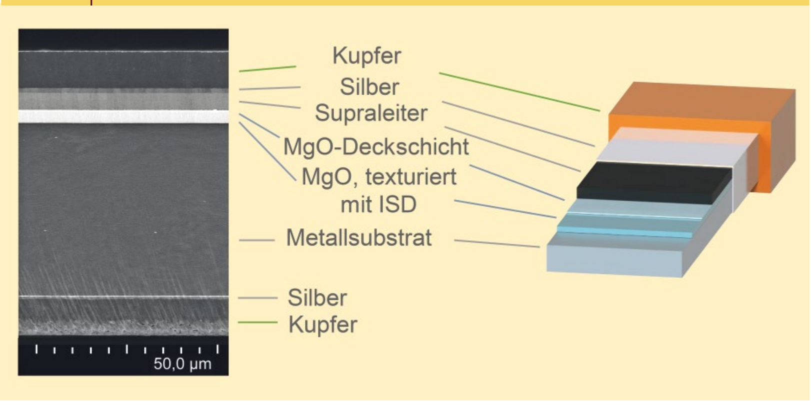


Three processes for producing the superconductor layer: a) physical vapour deposition (PVD) uses laser ablation, electron beam evaporation or ion sputtering to evaporate the material; b) metal organic chemical vapour deposition (MOCVD); c) solution deposition (CSD/MOD) [7].

polycrystalline substrate is used and a textured buffer layer is deposited on it. In addition, up to four further buffer layers must be used as diffusion barriers, adhesion promoters and to adjust the lattice constants. Several processes have also been developed for the production of the HTS layer (Figure 3). In addition to vacuum coating methods, there are also purely chemical methods. With all these methods, it is now possible to produce HTS tape conductors several hundred metres long with very good properties.

The only manufacturer of HTS tape conductors in Europe is THEVA Dünnschichttechnik in Ismaning near Munich, where one of the two authors worked as sales manager until recently. THEVA uses a combination of ISD buffer layer and PVD HTS coating (physical vapour deposition) in production (Figure 1). With this combination, it is possible to greatly reduce the number of coatings required. In addition to the ISD layer, which provides the necessary biaxial texture, only one top layer is necessary before the superconductor GdBaCuO is directly vapour deposited.

FIG. 4 | HTS tape conductor



Structure of the HTS tape conductor from THEVA. On the left, a cross-section taken with a scanning electron microscope; on the right, a non-scale 3D representation; the superconductor is $GdBa_2Cu_3O_{7-\delta}$.

In all manufacturing processes, the conductor is then surrounded by a silver layer approximately 1 µm thick. This is necessary to chemically protect the HTS layer, which reacts strongly with water, and to enable good electrical contacting of the ceramic. In addition, a copper layer is used or, alternatively, a thin copper foil is soldered on (figure 4). In addition to purely mechanical protection, this also ensures electrical stabilisation, which protects the superconductor from local overheating - "burning out" - in the event of an electrical overload.

Today, metal foils up to more than 1 km long, 10 or 12 mm wide and only 30 to 100 µm thin are used as starting material before coating. For cable applications, the tapes already coated with the superconductor are cut longitudinally to a width of 2 to 6 mm with roller cutters or lasers before copper plating.

High-temperature superconductors are hard-type-II superconductors. This means that magnetic flux penetrates the material in the form of quantised flux lines and is anchored there at so-called pinning centres. When an electric current flows, the Lorenz force acts on the flux filaments. Above a certain current, the critical current I_c, this force exceeds the pinning force density. The flux filaments begin to move, whereby losses occur, which leads to a voltage drop.

Usually, a voltage drop of 1 µV/cm is defined as the criterion for the critical current I_c. I_c depends on the temperature and the magnetic flux density. The lower the temperature, the greater the I_c. With increasing magnetic induction, on the other hand, the density of the flux filaments increases, so that the pinning force density is exceeded earlier and I_c decreases. Figure 5 shows this dependency exemplarily for an HTS tape conductor.

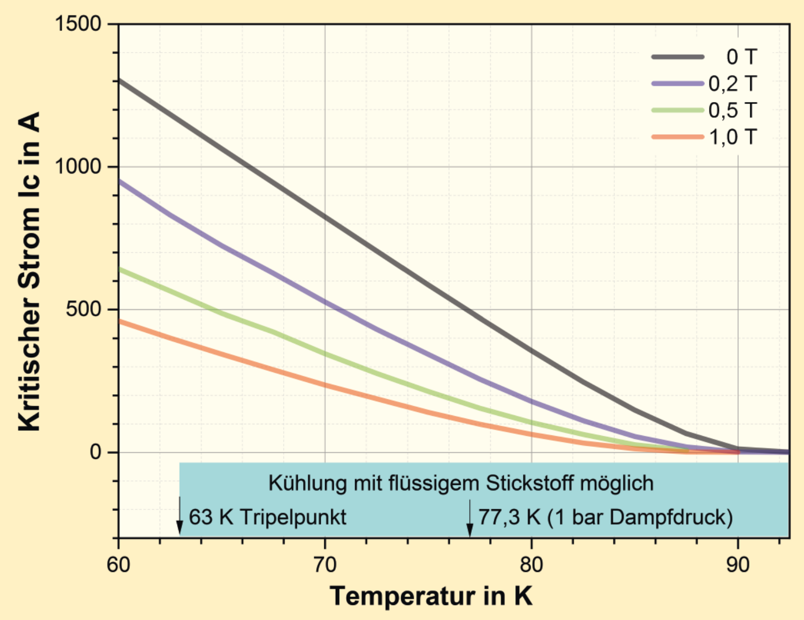
Consequently, when designing a cable as well as any other application, the temperature as well as the magnetic field generated by the operating current must be taken into account.

Usually, the critical current of the HTS tape conductors at 77 K and without an external magnetic field is measured as a reference value, because corresponding measuring devices are available. Subsequently, I_c at the required conditions in the cable is inferred on the basis of the dependency shown.

Typical values for the reference-I_c of 12 mm wide conductors and a thickness of approximately 0.1 mm are 500 to 800 A, narrower conductors carry correspondingly less current. Compared to copper conductors, this results in current densities 100 to 200 times higher, which enables cables with significantly higher current and power density.

Despite the increasing expansion of manufacturing capacities and more than ten companies worldwide developing such HTS tape conductors, production is not yet on a large industrial scale. Currently, only a few 1000 km of HTS tape conductors can be produced worldwide per year. However, this is already sufficient to equip larger cable routes in a reasonable time. By comparison, the production capacity for the low-temperature superconductor NbTi, as used in magnetic resonance tomographs, is already more than 100 000 km per year in a single factory. As demand increases, further expansion of the production of HTS tape conductors will further reduce their cost.

FIG. 5 | CRITICAL CURRENT



Critical current of a 12 mm wide HTS tape conductor as a function of temperature and magnetic induction directly at the superconductor. The direction of the magnetic field also has an influence on I_c. Here the dependence is shown for the most unfavourable orientation.

Structure of superconducting cables

Figure 6 shows the basic structure of superconductor AC cables. Usually, 4 mm wide tape conductors are helically wound onto the flexible inner tube. Depending on the current-carrying capacity, several layers of tape conductors may be required. Due to the extremely high current-carrying capacity of the superconductors, the outer diameter of the cable is thus only very slightly dependent on the rated current. This is followed by the electrical insulation, which can consist of paper laminated with polypropylene (PPLP). This is filled with nitrogen under pressure, which electrically results in a liquid-solid insulation whose use is possible up to the highest voltages.

In a three-phase concentric cable, the two further phase conductors then follow, including electrical insulation, before a normally conducting neutral conductor is applied. The transport of the liquid nitrogen as a coolant takes place as a forward conductor in the inner tube, while the space between the neutral conductor and the cryostat inner tube is suitable as a return conductor. Depending on the length of the cable, this can eliminate the need for a separate return line for the liquid nitrogen.

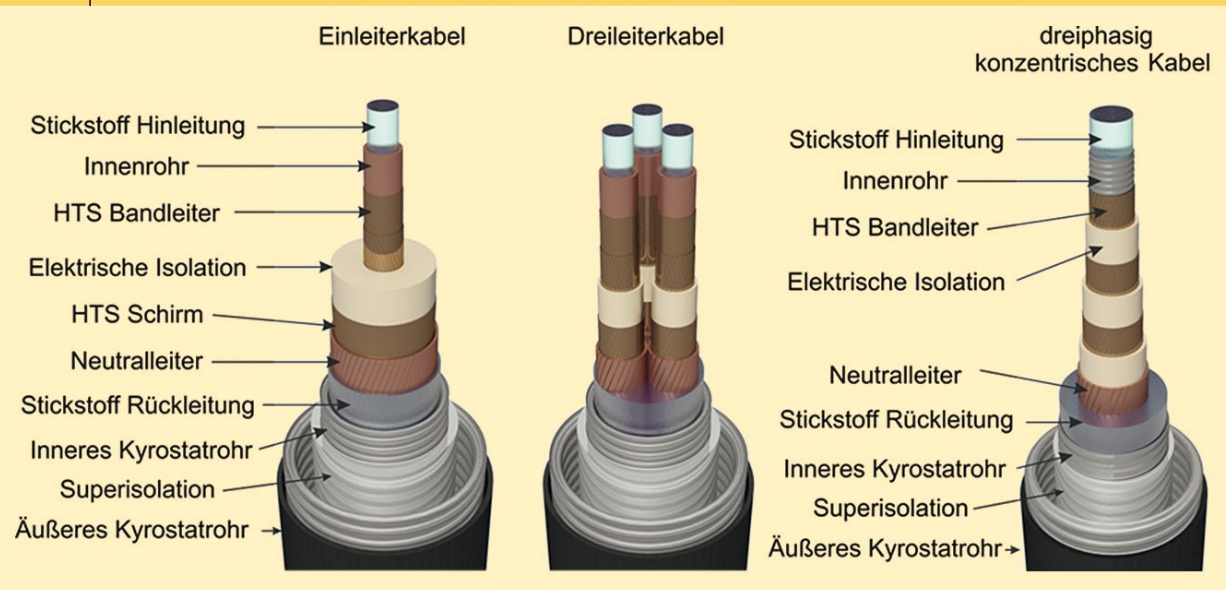
The three-phase concentric structure (Figure 6 right) is realised in set-ups of about 50 kV and is preferred over the other structures because of the lower superconductor requirement. With higher voltages, one then switches to the three-core cable (Figure 6 centre), as the three-phase concentric structure can no longer be sensibly realised due to the increasing insulation thickness. The three-core cable is typical for a voltage of about 110 kV and requires more superconductor than the three-phase concentric cable, but still manages with one cryostat shell for all three phases.

For higher voltages such as 380 kV, three strands of single-core cable are preferable, as the three-core cable would then also become very bulky. Depending on the cable diameter, all three cable types result in individual lengths between 500 and 1000 m, similar to conventional cables, before they have to be connected by a joint.

All cable types require thermal insulation, which is constructed in the same way. Seen from the inside out, it starts with the inner cryostat corrugated tube. Between this and the outer cryostat corrugated tube is a multilayer super insulation in a proper vacuum. This is necessary to minimise the heat input into the cable. With usual cable diameters and well-designed cables, values of only 1 W heat input per metre length can be obtained. The vacuum is generated by the manufacturer and can be guaranteed over a very long period of time, currently up to ten years. For some types of faults, the cable can be repaired on site and the vacuum restored. In principle, instead of flexible corrugated pipes, fixed pipes are also possible, which can then be laid together piece by piece.

In a superconducting cable, there is a pressure drop and a temperature rise of the liquid nitrogen between the

FIG. 6 | AC-cable



Basic construction of AC cables with high-temperature superconductors.

beginning and the end, which must not exceed the specified design values - for example 68-77 K at a few bar. This requires intermediate cooling after a certain cable length to bring the pressure and temperature back to the initial values. For AC cables, this limit is between 5 and 10 km for corrugated pipes, which can still be much exceeded with smooth pipes and DC cables. This means that today in inner cities a large number of cable routes are already possible without intercooling, because a very high proportion of the cable routes (more than 80 %) are only less than 5 km long.

All cable types must have a cooling system to transport the liquid nitrogen and dissipate the heat input. Basically, these systems are divided into open and closed systems. In classified as open systems, the nitrogen is kept in a large container and the demand is distributed into the cable by pumps. The nitrogen is then simply discharged into vented air. This type of cooling is very reliable, as shown in the AmpaCity project in Essen, where the 1 km long three-phase concentric cable requires refilling at intervals of about 14 days. More cooling power requires more frequent refilling, which at some point becomes impractical and makes a closed cooling system with a refrigeration unit necessary.

FIG. 7 This DC cable model with high-temperature superconductors of the 100 kA class at 20 K has an outer diameter of only 70 mm.

The technical feasibility of this type of cooling has already been demonstrated in a number of projects.

If hydrogen becomes established as a renewable energy carrier in the future, its liquid form will be very advantageous for some applications because of its high energy density. The temperature of 20 K then available is ideal in combination with the transport of electrical energy.

Since the current density of the superconductor can increase by a factor of 5-10 compared to 77 K [8], power in the gigawatt range can be delivered with very small outer diameters. Figure 7 shows a sample of a superconducting DC cable with a rated current in the order of 100 kA. This would allow transmission capacities of 1 GW to be realised even at a low voltage of 10 kV.

Advantages of superconducting cables

From the user's point of view, the advantages of superducting cables and lines can be divided into the three areas of laying and routing, the environment and operation.

Due to the very compact cable, the space requirement and the required route width can be significantly reduced.

For 380 kV cables, route widths of about 25 m are required, whereas a comparable superconducting cable would only require less than 7 m. In industrial applications, too, the compact cable results in simpler routing and installation. The effort required to lay the cable is reduced accordingly, and it can be done more quickly. A particular advantage results when the superconducting cable can transmit the same power at a lower voltage level. This can result in simplified approval procedures, which can lead to a significant acceleration in the implementation of the cable route.

If the cables are constructed as shown in figure 6, no stray electromagnetic fields occur during operation, as these are completely shielded by the superconducting screen. This means that in certain cases the cable can be laid less deep and the acceptance is increased. Moreover, a superconducting cable does not heat up the surrounding soil, because it takes on its temperature at its outer sheath. A possible drying of the soil and the use of well heat-conducting filling materials in the ground is thus avoided. In addition, depending on the load, a superconducting cable can reduce line losses and thus reduce the CO_2 footprint. Especially with DC lines and high currents, significant loss savings of significantly more than 50 % can be achieved.

In operation, superconducting cables and lines have the decisive advantage that they offer a much higher transmission power at a lower voltage level or that their transmission power can be significantly increased with the same outer diameter. The coaxial construction (Figure 6) and the resistance-free conductor result in a lower longitudinal impedance.

This enables a lower voltage increase in no-load operation, a lower voltage drop in operation and ultimately operation with so-called natural power. The latter means that significantly longer cable runs are possible with alternating current without compensation for reactive power.

This multitude of advantages is offset only by the additional expense of active cooling. Depending on the application, the advantages must be balanced against this disadvantage.

Versatile applications

Basically, the possible uses of superconducting cables and conductors can be differentiated into AC and DC applications (Figure 8). Since there are no AC losses in DC applications, longer lengths are possible without intermediate cooling and, depending on the current strength, simpler cable constructions are possible. For high voltage, a mixed liquid nitrogen and paper insulation is also advantageous for DC applications, as shown in figure 6 for an AC cable. Compared to solid insulation, fewer space charges are formed, making the electric field more homogeneous.

Since the typical lengths of individual cable sections in inner cities are only a few kilometres and their cooling has been successfully demonstrated, the state of development is already well advanced. In Essen, such a cable route with a length of one kilometre has been in continuous operation since 2014, and on Jeju Island in Korea, a 154 kV cable was successfully tested for a long time.

FIG. 8 | APPLICATIONS

	Längen pro Kabelstrecke bis zu	TRL 1	TRL2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Wechselstromanwendungen										
Innerstädtische Mittelspannung (6-30 kV)	Wenige km							X		
Innerstädtische Hochspannung (110-220 kV)	Wenige km						X			
Höchstspannungsübertragung (380 kV)	Wenige 100 km		X							
Höchstspannungsteilerdverkabelung (380 kV)	Wenige km		X							
Generatorausleitung (6-30 kV)			X							
Gleichstromanwendungen										
Elektrolyseindustrie (einige 10 kA)	Wenige 10 m					X				
Aluminiumindustrie (> 100 kA)	Wenige 100 m		X			X				
Datencenter	Wenige 10 m				X					
Anbindung erneuerbarer Energien	Wenige km					X				
Bahnstromversorgung	Wenige km						X			
Mittelspannungs-Gleichstromübertragung	~ 100 km		X							
Hochspannungs-Gleichstromübertragung	~ 100-1000 km		X							
Elektrische Flugzeugversorgungssysteme	~ 10-100 m			X						
„Degaussing" von Schiffen									X	
		Niedriger TRL			Mittlerer TRL			Hoher TRL		

Overview of superconducting cable applications and their current state of development according to the EU H2020 Technology Readiness Level.

FIG. 9 Superconducting 20 kA Power rail in a chlorine electrolysis plant in Ludwigshafen (Photo: Vision Electric SuperConductors GmbH).

In principle, it is now possible to develop this further to extra-high voltages of up to 380 kV, as is common in the European interconnected grid. The necessary high-voltage components have already been developed up to 300 kV.

However, no superconducting extra-high voltage cable is currently being used in a network. This application would be attractive, for example, in the partial underground cabling of extra-high voltage overhead lines [9], because the route width would be much reduced and, as already mentioned, the electromagnetic and thermal influence on the environment would be eliminated. The additional costs for the superconducting cable could also be kept low. In order to fulfill the old dream of transmitting the largest amounts of energy over long distances with almost no losses, the challenge of intercooling with cooling stations at the greatest possible distances would have to be tackled successfully. There are promising approaches to this, but so far not a single realised cable route.

Superconductors are ideally suited for DC cables and conductors, as the AC losses are eliminated and only the thermal losses of the cryo envelope determine the total losses. Very high currents of far more than 10 kA can also be realised, which have already been demonstrated several times. For example, a superconducting 20 kA busbar was tested experimentally in a chlorine electrolysis plant in Ludwigshafen. At the same time, the operational safety requirements could be fulfilled (Fig. 9).

A joint project funded by the Federal Ministry for Economic Affairs and Energy (BMWi) is currently developing the technology of a 200 kA superconducting busbar for aluminium plants. This could significantly reduce losses compared to the usual copper busbars. In Japan, there have been successful developments in direct current lines: In Ishikari, a 1000 m long 2.5 kA line connects a photovoltaic park with a data centre, and in a test station of the Japanese Railway Technical Research Institute, a 310 m long 1500 V DC cable was tested in railway power supply. A niche application is the so-called degaussing of military ships, for which the company American Superconductor (AMSC) in the USA has already installed the fourth system in a ship. Degaussing is intended to eliminate the ship's magnetic signature.

In principle, a superconducting cable could also be used for high-voltage direct current transmission. In the EU project BestPaths [10], a 30 m long cable section for 320 kV with a current carrying capacity of 10 kA was developed and successfully tested in 2018. Here, magnesium diboride was used as the superconductor, which requires cooling at 20 K. In the city centre of St. Petersburg, a 20 kV cable for a 2.5 kA medium-voltage DC link is about to be commissioned. Superconducting cables are also being developed for electrically powered aircraft to take advantage of the weight advantage.

All in all, it can be said that there are a large number of applications for superconducting cables and wires, for both alternating and direct current. The state of development depends on the respective application and the associated voltage level.

TAB. 1 | EVALUATION OF CONVENTIONAL SOLUTIONS OF AN HTS SOLUTION IN COMPARISON

Criteria	400 kV overhead line	Multiple system 110 kV XLPE cable[1]	400-kV-Cable	110-kV-HTS-Cable
Space-saving	☹	☹	☹	☺
Acceptance	☹	😐	☹	☺
Inexpensive	☺	☹	☹	😐
Technically mature	☺	☺	☺	😐
Capacity	☺	☹	☺	☺
Low loss	😐	☹	☹	☺

[1] **VPE:** Cable insulation made of cross-linked polyethylene.

Pilot project of Public utility Munich

Under the leadership of Stadtwerke München (SWM), the SuperLink joint project began in October 2020, in which the components of a superconducting 110 kV cable for 500 MVA are to be developed within two years and tested in practice for six months at the Menzing substation. Linde AG, the superconductor manufacturer THEVA, the cable manufacturer NKT, the University of Applied Sciences Südwestfalen and the Karlsruhe Institute of Technology (KIT) are involved. The project is funded by the BMWi.

If successful, a 12 km superconductor cable between the main substation in Menzing and the southern energy site in Sendling will be installed. Compared to conventional solutions, this is environmentally neutral and the disruption caused by civil engineering works in the centre of Munich can be significantly reduced. In most of the evaluation criteria (Table 1), the superconducting variant scores better. Only the technical maturity and economic viability have not yet been proven for this voltage level and cable length. However, because a costly tunnel construction in the city centre is avoided, as would be required for a conventional 400 kV underground cable, the superconducting cable could prove to be more economical.

Despite the very good progress, the development of superconducting cables and wires is not complete and some challenges remain. These include further improving the price-performance ratio of high-temperature superconductors, adapting cooling technology to longer cable runs, developing prototypes for higher voltages and higher currents, and demonstrating durable and initial commercial applications in grid or industrial use.

Summary

There are a large number of potential applications for superconducting cables and wires. High-temperature superconductors are commercially available today as good-quality tape conductors. Their average current-carrying capacity has roughly tripled in the last ten years, and further increases are foreseeable. The advantages compared to conventional solutions include significantly reduced electrical losses, high transmission power at lower voltages, as well as a drastic reduction in space requirements and the electromagnetic and thermal load on the environment. This considerably simplifies underground installation in inner cities, for example. The AmpaCity cable project in Essen has impressively demonstrated the durable and reliable operation of a superconducting cable. In the course of the energy transition, the framework conditions for energy-efficient and compact cables have developed very positively. The demand for renewal and expansion of the electricity grid has grown strongly at all voltage levels.

Keywords

High-temperature superconductors, superconducting materials, superconducting cables, high-current lines, alternating current transmission, direct current (DC) transmission, AmpaCity, SuperLink.

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Markus Bauer studied physics at the Technical University of Munich and received his doctorate there in 1998 in the field of high-temperature superconductivity. After several years at thyssenkrupp Transrapid, he moved to THEVA Thin Film Technology in 2010. There he was initially responsible for setting up tape production before taking over as head of business development in 2014. He has been Managing Director of thyssenkrupp Transrapid GmbH since April 2021.

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