# SUPERCONDUCTING LINKS FOR VERY HIGH-POWER TRANSMISSION BASED ON $MgB_2$ WIRES

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This paper presents the main technological achievements of the first 3-gigawatt-class HVDC superconducting cable system, which was manufactured and successfully tested in the European project Best Paths.
The technical focus is set on the cable conductor, the electrical insulation, and the high-voltage terminations. Furthermore, the implementation challenges of long-length systems are briefly outlined, along with environmental benefits and next steps for this new technology.

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## Introduction

Within the European project Best Paths that ran from 2014 until 2018 [1], one demonstration task investigated, built and qualified a high-voltage direct-current (HVDC) superconducting system operating at the multi-gigawatt level. The high transmission powers were motivated by recent studies demonstrating the need for additional pan-European corridors extending over several hundred kilometers and having capacities up to 20 gigawatts (GW) [2].

More specifically, a full-size 3-gigawatt-class superconducting DC cable system operating at 320 kV and 10 kA was demonstrated for the first time in Best Paths [3]. The cable is based on the magnesium diboride ($MgB_2$) superconductor, which is very economical to produce and is already commercially available in kilometric lengths. This is in contrast to ceramic-based superconductors that are based on more costly rare-earth components and have a complex manufacturing process.

The cable includes a fault-tolerant cable conductor, a high-voltage insulation layer and a cryogenic envelope. Apart from the cable itself, the complete system includes the cooling machine maintaining the temperature and the pressure of the cryogenic fluids, and two terminations to connect to the electricity grid. All these key components were specified, designed, developed and optimized for an industrial production during the project, providing manufacturing and assembling solutions that ensure feasibility, robustness, and practical usefulness. Although no joints were included in the project, an appropriate conceptual design already exists.

An important feature of the project was the consideration of the actual needs of the transmission system operators, in particular in the initial design phase. For instance, the input data provided by the French transmission system operator RTE was essential for the design of the cable conductor, as it specified the expected performance and behavior in the electricity grid, particularly under transient conditions.

[1] Best Paths project websites. www.bestpaths-project.eu and https://www.iass-potsdam.de/en/research/beyond-state-art-technologies-repowering-ac-corridors-and-multi-terminal-hvdc-systems-best.

[2] e-HighWay2050 project results, “Europe’s future secure and sustainable electricity infrastructure”. https://docs.entsoe.eu/baltic-conf/bites/www.e-highway2050.eu/e-highway2050/.

[3] A. Marian, S. Holé, N. Lallouet, E. Marzahn, and C. E. Bruzek, “Demonstration tests of a 320-kV-class DC superconducting cable for transmission of high powers”, IEEE Elec. Insul. Mag., vol. 36, no. 1, pp. 30–40, January 2020.

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The most important specifications of the cable system are summarized in Table 1.

Table 1. **Specification of the $MgB_2$-based HVDC cable in best paths**

| Parameters | Value |
|---|---|
| Power | 3.2 GW |
| Voltage | 320 kV |
| Operating DC current | 10 kA |
| Cooling medium | He gas for $MgB_2$ |
| | $LN_2$ for insulation and thermal shield |
| Cryogenic losses | < 0.2 W/m at 20 K in He gas |
| | < 2 W/m at 70 K in $LN_2$ |
| Current ripple | 1% amplitude at 50 Hz |
| Fault current | 35 kA during 100 ms |
| Power reversal ramp | 100 MW/s to 10 GW/s |

The following sections are focused on the main technological achievements of the project, namely design of the cable conductor and high-voltage insulation (Section II), concept of the electrical terminations (Section III) and testing of the demonstrator (Section IV). The last two sections are dedicated to long-length systems and environmental benefits, respectively.

## 2. Cable design

The different design options for a superconducting cable system are discussed in detail in reference [4], which also presents the decision-making process carried out in Best Paths. The chosen cable design is schematically shown in Fig. 1, with the main components indicated accordingly.

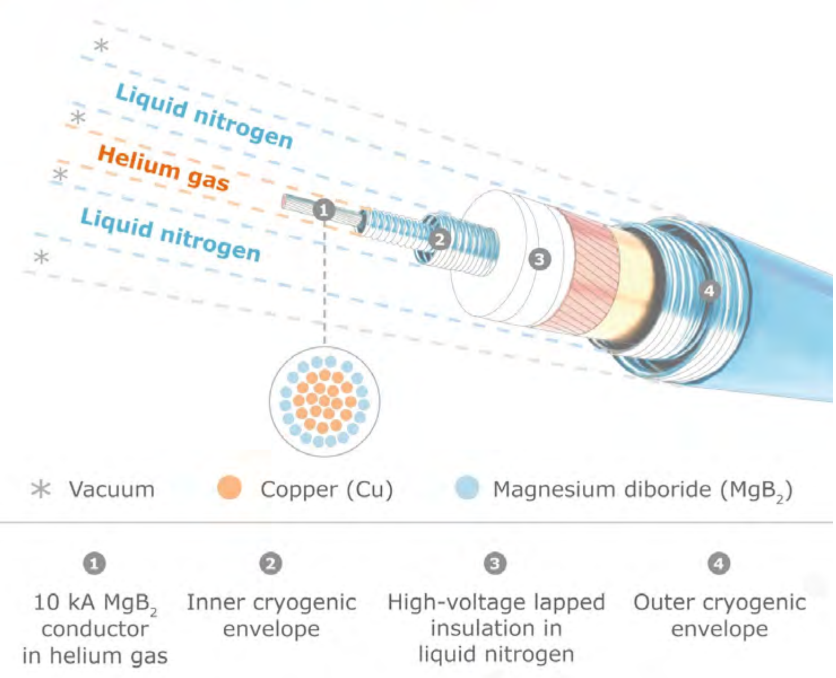


**Fig. 1.** Sketch of the 3.2 GW $MgB_2$ cable system showing the key components. The electrical terminations are not represented here.

A. Cable conductor

To ensure the superconducting properties of the $MgB_2$ material, its operating temperature needs to be maintained in the range of 15 to 25 K (~ -250°C). This temperature range can be reached by using gaseous helium or liquid hydrogen. In the project, gaseous helium was selected as a coolant for the cable conductor, as the Nexans test platform is not equipped for testing in an explosive environment. A commercial cryogenic line was used for circulating the cooling fluids. These cryogenic envelopes have already been in use on industrial and large-scale scientific sites for several decades. They are flexible and can be produced in kilometric piece lengths. Their performance and characteristics are detailed in [5].
As shown in Fig. 1, the cryogenic line includes an external thermal shield actively cooled by liquid nitrogen ($LN_2$) in the temperature range of 70 to 80 K, and two vacuum thermal insulation chambers to reduce the heat

[4] J. Muñoz-Antón, A. Marian, F. Lesur, and C.-E. Bruzek, "Dichotomic decision optimization for the design of HVDC superconducting links", Entropy, vol. 22, Art. no. 1413, December 2020.

[5] S. Klöppel, A, Marian, C, Haberstroh, and C.-E. Bruzek, "Thermo-hydraulic and economic aspects of long-length high-power $MgB_2$ superconducting cables", Cryogenics, vol. 113, Art. no. 103211, January 2021.

inleak into the cable. The $MgB_2$ conductor is itself housed in the innermost helium-cooled cryogenic envelope whose outer wall is lapped with high-voltage insulation.
The cable conductor is assembled by helically winding 18 $MgB_2$ wires around a flexible copper core. Its bare diameter is around 9.5 mm. Fig. 2 shows the conductor cross section and details of one of the $MgB_2$ wires developed for the project. A critical current of up to 14 kA at 20 K in self-field has been found, which is in accordance with the expected behavior.

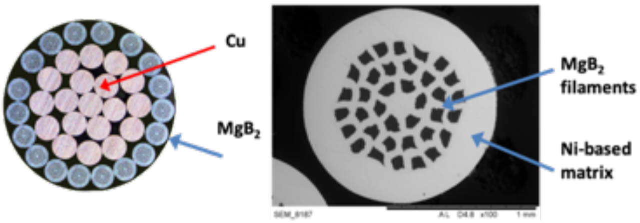


**Fig. 2.** Picture of the 10 kA cable conductor consisting of 18 $MgB_2$ wires wound around a copper core (left) and one $MgB_2$ wire composed of 36 superconducting filaments embedded in a matrix of nickel and monel (right).

Analytical and finite-element modeling were used to design, enhance, and validate the cable structure under the transient grid conditions listed in Table I. For instance, modeling is used to check that the losses generated by ripples can be considered as negligible and that during the power reversal ramp the cable does not present any risk of quenching for ramp values lower than 5 GW/s which cover most of the specification range [6].
Numerical simulations were also employed to optimize the amount of copper required for efficient protection of the cable conductor during a fault. The copper core acts as a low-resistance electrical shunt protecting the superconducting wires. Thus, the resistive wires transport the inrush current in excess of the superconducting critical current during the fault clearance. Since the copper core has a very low resistance at 20 K (RRR >150), it can accept high fault currents (35 kA). However, during such a fault, the Joule effect causes an increase in temperature and the cable must be rapidly disconnected to prevent any damage. A typical fault clearance requires less than 100 ms, and the acceptable temperature rise during and after fault was shown to be maximum 100 K.

[6] C. E. Bruzek et al., "Cable conductor design for the high-power $MgB_2$ DC superconducting cable project of BEST PATHS," IEEE Trans. Appl. Supercond., vol. 27, no. 4, Art. no. 4801405, June 2017.

As soon as the fault is cleared, the cooling system returns the operating temperature to 20 K. This cooldown operation can take several minutes. Apart from the conceptual design, specific work has been carried out at ASG Superconductors and Nexans concerning the $MgB_2$ wires and cables, which are now ready for large-scale deployment. As the cable is very compact, the operating current level is easily adjustable to grid requirements by simply adding or removing one or several wires.
For the future electricity grids, hundreds of kilometers of HVDC cables are envisioned, which will require a large quantity of superconducting wires. $MgB_2$ wires are based on abundant and low-cost materials and a fully industrial manufacturing process, making them a good candidate for bulk production. The length of a single piece was optimized to 2 km, with a highly reproducible level of the critical current and wire diameter. ASG is now able to produce several hundreds of kilometers of such a wire. A 2 km piece is well suited both for the industrial cabling process and for the grid installation requirements that permit a limited number of cable joints. Beside the industrialized strand production, the cable itself was manufactured on standard industrial cabling machines, as illustrated in Fig. 3. After adjustment of the cabling tooling, no critical current degradation was detected on the wires extracted from the cable.

**Fig. 3.** Planetary cabling machine from Nexans used to manufacture the cable conductor for Best Paths (courtesy of Nexans).

At the end of the project, several hundreds of meters of cable conductor have been produced, demonstrating the high reliability of the $MgB_2$ wire and cable manufacturing processes.

## B. High-voltage insulation

The HVDC system requires a simultaneous operation at both high current and high voltage. A thick dielectric material is necessary for the voltage insulation between the pole and ground. This insulation should present a high voltage breakdown strength and could be similar to the dielectrics used for resistive cables, made out of polyethylene or polypropylene layers.

If the dielectric is located outside the cable cryostat, the insulation will operate at room temperature in a so-called "warm dielectric" design [7]. Another option is to place the high-voltage insulation as close as possible to the cable conductor at cryogenic temperature, in a so-called "cold dielectric" design [8]. This second option was selected for the Best Paths demonstrator because it presents some advantages for cryogenic management and installation.

**Fig. 4.** Picture of the demonstrator successfully tested in Best Paths.

[7] A. Morandi, M. Marzinotto, and G. Mazzanti, "Feasibility of high voltage DC superconducting cables with extruded warm dielectric", in Proceedings of the 2014 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Des Moines, IA, USA, 19–22 October 2014, pp. 796–799, DOI: 10.1109/CEIDP.2014.6995878.

[8] A. Marian, S. Holé, F. Lesur, M. Tropeano, and C. E. Bruzek, "Validation of the superconducting and insulating components of a high-power HVDC cable", IEEE Elec. Insul. Mag., vol. 34, no. 1, pp. 26–36, January 2018.

As illustrated in Fig. 1 and Fig. 4, the insulating material is placed just outside the inner cryogenic envelope and housed inside the outer cryogenic envelope. The dielectric material is a lapped insulation that operates in $LN_2$ at 70 K. Paper lapped insulation is a standard material for the cable industry and has been used in very long submarine cables impregnated with oil. In our cold dielectric design, $LN_2$ replaces the oil. In addition to its efficient cooling properties, $LN_2$ also has good dielectric strength properties. To benefit from these properties, a Kraft paper lapping maintains a porous space that is impregnated by $LN_2$ during the cable cooldown.

A thorough analysis of DC breakdown mechanisms and space charge characterization have been carried out in the project [3, 8]. It has been found that Kraft paper impregnated with pure $LN_2$ (no gas bubbles) shows high dielectric performance (electric field breakdown > 30 kV/mm measured on thick layer). Kraft paper is also tolerant to the presence of internal defects such as holes. For limited damages, thanks to the high dielectric strength of $LN_2$, the insulation recovers its initial dielectric properties after a breakdown when "fresh" $LN_2$ refills again the damaged space. Furthermore, it was also shown that no trapped space charge can migrate or accumulate within this material, which gives good confidence in its long-term reliability.

Therefore, a high-voltage insulation based on Kraft paper impregnated with $LN_2$ is robust and is recommended as a dielectric material for superconducting HVDC systems, as soon as no $N_2$ gas bubbles are generated.

## 3. Terminations

The main target in the development of HVDC terminations was to demonstrate the 320 kV voltage class in DC while accommodating the $MgB_2$ superconductor at 20 K. Generally, terminations need to fulfil two main functions: (I) secure the injection of the high current and high voltage from the grid to the superconducting cable, and (II) transfer the pressurized cryogenic fluids from the cooling system to the cable. The termination includes a special current lead providing a transition zone between resistive and superconducting materials. This transition zone is optimized to maintain low thermal conduction losses in the cryogenic fluids of the system despite the significant Joule losses from high current flow in the resistive part. The termination also manages the electric field stress between the high voltage at its top and the ground potential at its bottom.

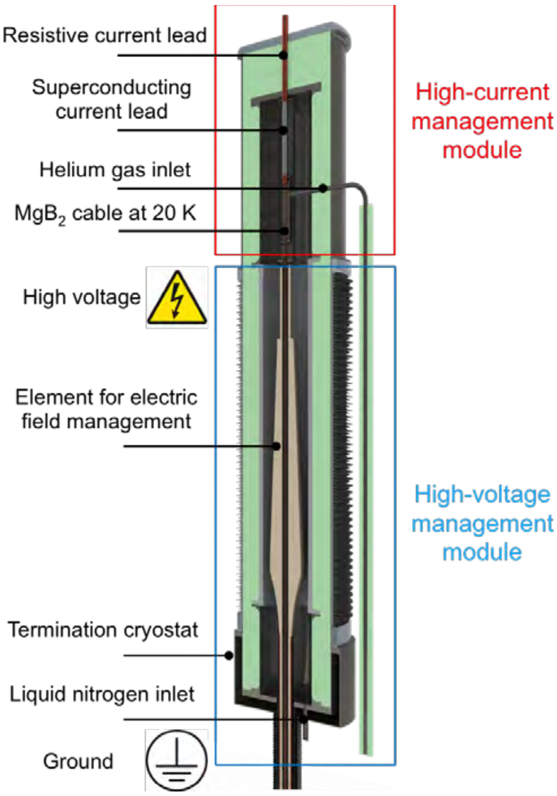


**Fig. 5.** Sketch of the HVDC termination developed for Best Paths, highlighting its modular design.

The design of the termination is innovative, as it effectively separates the current and voltage functionalities, resulting in a strong modularity of this accessory. As shown in Fig. 5, the termination is split into two fully independent parts: in the upper part the current is injected through the special current lead connected to the cable conductor, while the high-voltage gradient is attended to in the lower part. This design is evolutive and can easily be adapted to different voltage and current values. For instance, if the operating current of the system changes, only the upper part of the termination has to be modified, whereas the lower part remains unaffected, and vice versa.

[9] Cigré working group B1.31 convened by D. Lindsay, "Recommendations for testing of superconducting cables," Cigré Technical Brochure 538, June 2013.

[10] Cigré working group B1.32 convened by B. Sanden, "Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500 kV," Cigré Technical Brochure 496, April 2012.

## 4. HVDC Testing

No standard has been yet established for testing HVDC superconducting cables. Some useful recommendations are given by the Cigré brochures [9; 10]. The combination of these two sets of good practices constituted a basis for proposing a testing methodology for the Best Paths superconducting demonstrator. Moreover, the resulting protocol for the HVDC tests was shared with and accepted by the transmission system operators who were partners of the Best Paths project. Along with the testing protocol, the measurements and results obtained within Best Paths hence constitute a significant step toward preparing a new standard for testing super-conducting HVDC cables prior to their installation in the electricity grid. The high-voltage testing was carried out at an industrial test platform on a 30-meter superconducting loop connected to two terminations. It was conducted at up to 592 kV, which is the testing voltage required to qualify 320-kV-class systems. The test platform arrangement is presented in Fig. 6, and an in-depth description of the testing protocol and results is reported in [3].

**Fig. 6.** Testing loop shown together with the 800 kV DC generator on the Nexans testing platform (courtesy of Nexans).

Note that the small cooling systems that provided overcooled $LN_2$ and helium gas were specifically designed for the testing loop. The cold power and mass flow were therefore adjusted according to the hydraulic parameters of the loop. In the future, the specification of these machines should be reexamined according to the length of the link under consideration.
The loop elements of the manufactured cable system successfully passed the testing program for the 320 kV class without any breakdown. This confirms the availability of the superconducting HVDC cable technology for transmitting bulk power higher than 6 GW (for bipolar systems). These innovations also open new possibilities to design superconducting DC links for the future.

## 5. Implementation toward long-length HVDC cable systems

Best Paths has demonstrated operation of gigawatt-scale systems on industrial test platform using a "type test" strategy. However, in practice, an HVDC link can be several hundreds of kilometers long, built with several segments connected in series. This requires field joints to extend the electrical and the hydraulic circuits. These elements have already been conceptualized but should be prepared and experimentally tested with the same testing protocol as the loop.
In addition, several large cooling and pressurization stations are required to maintain the cryogenic conditions for the superconducting link. They should be distributed along the link to keep the cooling fluids in the temperature/pressure ranges of 15-20 K / 10-20 bar and 70-100 K / 3-15 bar for helium and $LN_2$, respectively. As a superconducting cable does not generate Joule losses, the energy cost required for these devices is the only operating cost of the system.
The span between two cooling stations depends on the available space for installation and the local elevation of the link. To install long links, adjustments of the cryogenic envelope diameter are also required. Different scenarios are presented and discussed in [5]. With the existing cryogenic machines and lines, a span between two cooling stations of up to 50 km is achievable. However, investment costs are reduced if the distance is reduced to the range of 10-20 km.
All required technologies and equipment are commercially available at this point. As an example, the AmpaCity cable system in Essen [11] has been operating in the electricity grid since 2014 with 100% availability, energizing a full district close to the city center. Furthermore, large cryogenic machines and circulation pumps have proven their reliability

[11] M. Stemmle, F. Merschel, M. Noe, and A. Hobl, "AmpaCity project—Worldwide first superconducting cable and fault current limiter installation in a German city center", in Proceedings of the 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), Stockholm, Sweden, 10–13 June 2013, DOI: 10.1049/cp.2013.0905.

and robustness during several decades of operation in high-energy applications [12], at even lower temperatures (1.8 K) than the one needed for $MgB_2$.
Conservative economical models proposed in [5] indicate that the proposed superconducting link is economically viable both in terms of investment and operation costs for transmitted powers higher than 3 GW, when compared to a resistive link. For the concrete case of a 6.4 GW link with a length of 500 km, a comparison of the capital costs can be seen in Fig. 7. The $MgB_2$-based superconducting link is overall 27% less expensive than the resistive solution. This is primarily due to the small footprint of the superconducting link, which leads to a reduction in the expenditure on civil engineering and right-of-way by a factor of 2.6. The capital cost is very similar for both links, whereby the superconducting system also includes the cooling stations. Furthermore, the technology and cost of the converters that deliver 320 kV and 10 kA is identical for both solutions.

[12] S. Claudet, P. Gayet, P. Lebrun, L. Tavian, and U. Wagner, "Economics of large helium cryogenic systems: Experience from recent projects at CERN", in Advances in Cryogenic Engineering, Q.-S. Shu, Ed., Springer: Boston, MA, USA, 2000, pp. 1301–1308.

[13] A. Marian et al., "An $MgB_2$ HVDC superconducting cable for power transmission with a reduced carbon footprint", in Eco-design in Electrical Engineering: Lecture Notes in Electrical Engineering, J.-L. Bessède, Ed., Springer: Cham, 2018, pp. 129-135

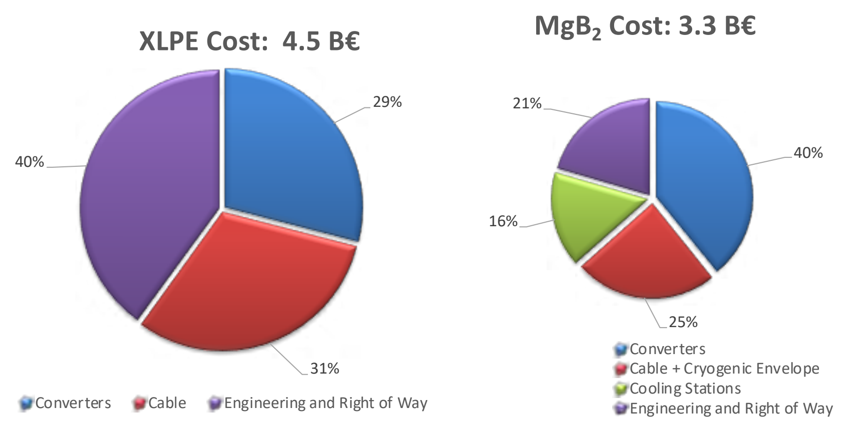


**Fig. 7.** Capital costs of resistive XLPE cables and $MgB_2$ superconducting cables for a 6.4 GW DC power link with a length of 500 km.

## 6. Environmental and neighborhood benefits

A life-cycle assessment (LCA) of the environmental impact of the HVDC superconducting cable system determined a strong reduction of most the considered indicators [13].
As the cryogenic envelope completely eliminates thermal dissipation to the surrounding area, superconducting power links can be laid underground in a confined environment. By contrast, the current rating of resistive cables is decreased by mutual heating between adjacent circuits.

The absence of heat dissipation and the compact design offer a significant advantage for superconducting cables in areas with high ambient temperature, or when crossing busy urban districts, or within forested or pristine areas.
In addition, their compact size and reduced footprint are clearly highlighted in Fig. 8, which shows that one pair of high-power superconducting cables has the same transmission capacity as eight resistive cables. This leads to a reduction of the footprint by a factor of 10 and expedites the permitting process.


Fig. 8. Comparison of the environmental footprint of resistive XLPE cables and $MgB_2$ superconducting cables for a 6.4 GW DC power link.

## 7. Conclusion and next steps

A gigawatt-scale HVDC superconducting cable system was designed and tested in Best Paths. Based on $MgB_2$ superconducting wires, this system was shown to be technologically mature and cost competitive for bulk power transmission.
With their high efficiency, compactness and reduced environmental impact, superconducting cables offer several technological advantages that are likely to find high public acceptance. An important next step will be to develop testing guidelines for HVDC superconducting cables to guarantee safety and quality standards.
Only the operation of such a high-power cable in real-life grid conditions will confirm the full potential of this technology in a definitive manner.
In this respect, the involved partners recommended at the end of the project that appropriate de-risking instruments for the transmission system operators be put in place within the framework of European energy-climate policies.
The Best Paths demonstrator was designed to operate in gaseous helium as a cooling medium. Based on the developed design, the coolant can be replaced by liquid hydrogen in future prototypes. In addition to electricity transmission, such a superconducting cable system would also offer a smart and safe option for storing and distributing large amounts of hydrogen under low pressure. Pending issues involve the necessary risk management associated with the use of hydrogen along with the testing and certification of the relevant equipment by authorized bodies. Lastly, an experimental investigation of the dual transport of these energy carriers – hydrogen and electricity – would support the European Green Deal agenda.

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