The BEST PATHS Project on MgB_2 Superconducting Cables for Very High Power Transmission

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***Abstract*—BEST PATHS (acronym for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal HVDC Systems") is a collaborative project within the FP7 framework of the European Commission that includes an MgB_2-based power transmission line among its five constituent demonstrators. Led by Nexans and bringing together transmission operators, industry and research organizations, this demonstrator aims at validating the novel MgB_2 technology for very high power transfer (gigawatt range). The project foresees the development of a monopole cable system operating in helium gas in the range 5–10 kA/200–320 kV, corresponding to a transmitted power from 1 to 3.2 GW. The main research and demonstration activities that will be pursued over the four-year project duration are: 1) development and manufacturing of MgB_2 wires and of the cable conductor; 2) design and manufacturing of the HVDC electrical insulation of the cable; 3) optimization of the required cryogenic system; 4) electromagnetic field analysis; 5) design and construction of a prototype electrical feeding system including terminations and connectors; 6) testing of the demonstrator; 7) study of grid connection procedures and integration of a superconducting link into a transmission grid; and finally, 8) a socio-economic analysis of the MgB_2 power transmission system. CIGRÉ recommendations will be used to take into account the established international practices, and guidance will be given on newly addressed technical aspects. An overview of the project is presented in the paper, including the main tasks and challenges ahead, as well as the partners and their roles.**

***Index Terms*—BEST PATHS, high-power transmission lines, HVDC, MgB_2 cables, superconducting links**

BEST PATHS is supported in part by the European Commission within the 7th Research Framework Programme, Grant Agreement 612748. *(Corresponding author: Adela Marian.)*

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I. Introduction

TRANSMISSION SYSTEM OPERATORS (TSO) are responsible for the balance between electricity generation and consumption, at any time. While the power demand has been increasing for decades, the present situation in Europe tends towards stabilization [1]. Nevertheless, the integration of large amounts of renewable energy across the European continent is a real challenge [2]. In addition, interconnecting countries seek to guarantee security of supply (sharing risks as well as capacity reserves) and to trade energy across borderlines at the best price. All these factors require the development of bulk power corridors. As the building of such infrastructures necessitates many years and significant investments, a prior assessment of the needs and constraints is essential. For example, the recent interconnection between France and Spain (2 x 1000 MVA, 65 km, 2015) was built fully underground as a high-voltage direct-current (HVDC) line, after around twenty years of strong public opposition to the installation of 400 kV overhead lines [3]. The global investment was 700 M€.

The importance of bulk power lines of hundreds of kilometers length was also emphasized by the recent outcome of the EU FP7 e-Highway2050 project [4]. The need for 5 to 20 GW pan-European transmission corridors was clearly identified; in particular, major North-South corridors and connections of peninsulas and islands to continental Europe were shown to be critical.

In recent years, the necessity to limit the visual impact of long-distance transmission lines has brought about a remarkable evolution of the underground circuits. For example, 97% of new high-voltage lines (63 to 90 kV) in France were buried between 2012 and 2014. While the number of underground lines longer than 10 km was negligible in 2007, more than 72% of the installed circuits between 2014 and 2016 will be longer than 10 km, and 27% longer than 20 km.

The conventional solutions presently used to transmit power in the range of 1 to 8 GW include overhead lines, underground cables with extruded insulation (XLPE), and gas-insulated lines (GIL). Most often they require large rights of way and/or extensive civil engineering. By contrast, the compactness of superconducting cables is an attractive feature that entails narrow corridors and reasonable trenches. Furthermore, existing buried links are subject to limitations in terms of transmitted power and length. For example, the longest XLPE link has a length of 39.8 km (Shinkeiyo-Toyosu, Japan, 2.4 GW) [5], whereas the highest power for a buried GIL is 4.4 GW (Kelsterbach, Germany, but only 0.9 km long) [6]. Superconducting links do not suffer from these limitations.

In fact, superconductors have been ready for deployment in energy-related applications for some years now, but have yet to be utilized on a large scale and still need to be validated for DC system operation. Within the BEST PATHS European project, the main goal of the demonstrator called DEMO 5 is to investigate whether superconducting HVDC links are a viable solution for bulk power transmission in the future grids. This demonstrator will also be a first attempt to employ MgB_2 as a superconductor for HVDC cables. Due to the low cost and high transport current of the MgB_2 wires at the magnetic field of interest for energy transfer applications, these cables are expected to be competitive not only with conventional resistive XLPE cables, but also with high-temperature superconducting (HTS, e.g. Bi-2223 or YBCO) cables. Hence, we aim to investigate the technological maturity of MgB_2 HVDC links for operation in the grid.

II. Description of the Project

The potential of the MgB_2 superconductor for application to high-current energy transmission (> 10 kA) was demonstrated at CERN in 2014, when two 20 m long copper-stabilized MgB_2 cable assemblies were connected in series and were successfully operated in DC mode at 20 kA at 24 K. The measurements were conducted at an *ad-hoc* constructed installation that allows for the electrical characterization of superconducting cables cooled with helium gas, at any temperature in the range of 5 K to 70 K and at DC currents of up to 20 kA [7]–[9].

In addition to the high-current capability demonstrated at CERN, DEMO 5 aims to develop an HVDC monopole superconducting cable designed to operate in the range 5–10 kA/200–320 kV, corresponding to a transferred power of up to 3.2 GW. The superconducting system will have a significantly reduced environmental footprint with respect to a conventional line, due to its compact cryogenic envelope, which results in an overall small size.

The high-current cable conductor will be built by stranding together MgB_2 wires, which recently became available in long unit lengths. As part of the demonstration activity, a cryogenic cooling system allowing for operation of the cable in helium gas in the range of 15 K to 25 K and at 20 bar will be designed and manufactured for the test of the superconducting line. To keep the thermal losses at an acceptable level, a liquid N_2 thermal shield will be added to the cryostat housing the cable.

The superconducting wires will be produced by Columbus Superconductors through the Powder in Tube ex-situ process [10], with a layout that will be defined as the most suitable for this kind of application. The possibility to produce round MgB_2 wires in kilometer lengths has already been demonstrated after many years of technical collaboration between Columbus and CERN and with Nexans. The preliminary wire is a monel-nickel sheathed round wire with a diameter of around 1.3 mm, containing 36-37 MgB_2 filaments with a filling factor of 13% to 16% of the total surface. Several kilometers of wires will be manufactured to qualify the production process and detailed investigations and characterization will be carried out in collaboration with CERN to check the homogeneity of the performance. Before starting the cabling activities, stress tolerance of the wire subjected to bending and tension will be extensively studied as well.

A simple geometry for a compact cable conductor able to transfer more than 10 kA at 20 K, and appropriate for use in the grid, is shown is Fig. 1. The conductor contains 24 round MgB_2 wires twisted around a flexible multi-strand copper core, and it can be easily connected due to the superconducting wire location in the outermost layer. The external diameter of this conductor is about 12.5 mm.

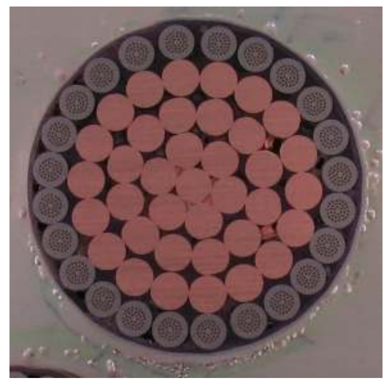

Fig. 1. Design for a possible cable conductor, consisting of an outer layer of 24 MgB_2 wires (shown in grey) and a core of 37 copper wires (shown in red).

The cryogenic envelope will consist of multiple concentric tubes. More specifically, corrugated tubes will be used, because a certain degree of flexibility is needed for the cable installation. Such tubes are routinely manufactured in hectometer lengths, delivered on drums and can be joined on site for multi-kilometer-long systems. Since the goal is to have an overall thermal load lower than 1 W/m at 20 K, a rather sophisticated insulation design will be necessary, consisting of high-vacuum insulation combined with several layers of multilayer insulation and the already mentioned active-shield cooling by liquid nitrogen. The thermal heat leak from room temperature will determine the overall required cooling power, as the AC losses of a DC system are greatly reduced when compared to an AC cable. In the eventuality of a fault current, the proposed cable conductor design will result in a limited heat generation during the ensuing quench.

Appropriate cooling machines optimized for this type of application are already commercially available. For the demonstrator, a refrigerator capable of delivering 120 W at 20 K and circulating gaseous He at 20 bar is under procurement, and will be commissioned in early 2016.

The reliability and availability of the system are of key importance for its acceptance by TSOs. During the second part of the project, specific vision studies for very long systems (>100 km) will be carried out to investigate the future technologies for the cryo-envelope and for possible cooling systems operating with gaseous He or liquid H_2. The level of system availability is dependent on the cooling power and on the redundancy of the cryogenic fluid management systems, which can have a significant impact on the investment costs for the system. A Turbo-Brayton cooling cycle will be the first candidate for an efficient and reliable cooling cycle for long-distance systems. The thermo-hydraulic design aims at ensuring minimum values of the thermal load and of the pressure drop along the line. Moreover, minimization of the number of cooling stations is essential for an efficient operation over very long distances and for decreasing the investment costs.

These results will be used for an economic viability analysis of the proposed superconducting HVDC cable solution, taking into account not only the cost for the cable itself, but also estimated costs of the substations and civil engineering. A comparison with resistive solutions and HTS-based solutions for relevant case studies proposed by TSOs will also be included.

III. Main Challenges

A. *Testing the demonstrator*

The high-voltage test of the superconducting system will be conducted at the Nexans HV cryogenics platform in Hanover, according to the CIGRÉ recommendation B1.31 [11] and to current standards for conventional DC cables. The size of this testing station limits the cable length to a maximum of 20 m. The high-current tests (up to 20 kA) of the 20 m long prototype will be carried out at CERN. Transient operation modes as derived from grid operation requirements will be analyzed and tested.

B. *Liquid-nitrogen-impregnated lapped HVDC insulation*

In the following, the cable is defined as the conductor inserted into the inner helium-cooled cryogenic envelope whose outer wall is lapped with high-voltage insulation. The insulating tapes are wrapped around a flexible filling layer that smoothens out the waves of the corrugated tube surface and allows for bending deformations. This layer is prepared according to proven techniques used for the AmpaCity project [12]. In this configuration, the inner cryostat cannot slide out of the cable dielectric for possible repair work. However, as the cable is intended for very long power links, it will likely be laid in an open trench. Its installation can therefore be carried out with very limited risk to the inner cryostat. In the proposed concept shown in Fig. 2, the cable is housed in an outer flexible cryogenic envelope, which is cooled by liquid N_2 acting as a thermal shield. Thus, the insulating tapes will be impregnated with liquid N_2 in the fashion currently employed for oil-impregnated conventional cables. The material foreseen for the electrical insulation is polypropylene laminated paper (PPLP) tape, whose mechanical properties enable lapping. To limit the risk of a dielectric breakdown, gas bubble formation in the cooling liquid of the HV insulation should be avoided. As a result, the liquid N_2 will be pressurized at up to 5 bar and subcooled at about 70 K.

Given that the cable system operates in DC mode, a dedicated experimental setup will be developed for testing the HV insulation performance, with a particular focus on space-charge distributions. Measurements will be performed using the pressure-wave-propagation (PWP) method [13], while the cable is electrically stressed up to 60 kV in liquid N_2 at a pressure of 5 bar and at variable temperature. For safety reasons the testing voltage will be lower than the operating voltage of 320 kV. However, the thickness of the insulator will be correspondingly reduced to maintain an electric field that is equal or even larger than the one in operating conditions.

In the PWP method, a short-duration pressure pulse is transmitted to the insulator and moves the charges encountered during its propagation. The resulting local current due to the charge displacement is detected in the measurement circuit connecting the insulator electrodes. The current amplitude measured at a given time is proportional to the charges displaced at the position of the pressure pulse at that time. As a consequence, the signal profile is an image of the space-charge distribution, time and position being simply connected by the speed of sound. The pressure pulse acts then as a probe of the charge density. Due to the cryogenic environment, it is not possible to use lasers for generating the pressure pulses, therefore a dedicated pressure-pulse generator will be designed [14]. Additionally, as the layered structure of the tested insulator could perturb the propagation of the pressure wave and the signal generation, specific signal treatment will be required [15].

It is the first time that measurements will be carried out under such harsh environmental conditions. The experimental setup developed here could not only validate the insulation structure of the proposed BEST PATHS cable, but could also open the door for new cable structures as well as new insulation studies.

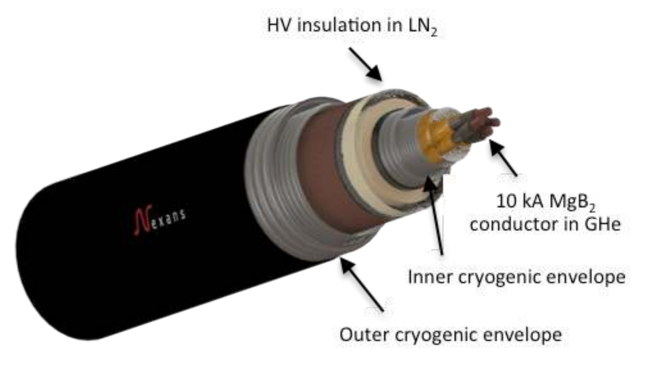

Fig. 2. The HVDC cable concept for the Best Paths project, schematically illustrating the cable conductor housed in the inner cryogenic envelope at 20 K, which is wrapped with HV insulation tapes and inserted into the outer cryogenic envelope at 70 K.

C. *Designing the terminations*

Cryogenic electrical terminations will be designed for the demonstrator, and will be optimized both for electric-field management and for thermal management. For the former, cryogenic bushings will be employed, based on prototypes built for HTS cable conductors, which have already been tested by Nexans and require only minor modifications.

Innovative solutions are needed for the thermal management, since this will be the first instance where a flow of cold He gas at 20 bar is injected at HV in association with high current. The heat inleak at 20 K should be as low as possible for a cost-competitive and robust concept.

For the current injection, the proposed concept will include a hybrid current lead consisting of two parts: a copper upper part making the transition from ambient temperature to an intermediate chamber cooled at 70 K in liquid N_2, and a lower part extending the lead from 70 K to 20 K with a superconducting barrel made out of HTS BSCCO tapes. Thus, most of the heat load will be intercepted by the low-cost liquid N_2. This design entails managing an estimated heat load lower than 5 Watts on the 20 K cooling system.

For the He gas flow injection, a special tube will be installed parallel to the current lead, connecting the electrically grounded cooling machine to the cable conductor at 320 kV electrical potential. This injection tube will include cryogenic thermal insulation in its radial direction and high-voltage management in its longitudinal direction, in order to reduce the heat load on the 20 K cooling system. The tube is currently under study, with first experimental tests to be conducted soon.

D. Simulations and modeling

The simulation task in the project will be carried out by KIT and is dedicated to investigating the electromagnetic behavior of the MgB_2 cable conductor. In particular, the power dissipation caused by transients of the transmitted power and by AC ripples will be studied. The latter are a common consequence of the AC/DC rectification process. In order to perform these investigations, a numerical model solving the time-dependent Maxwell's equations using the finite-element method will be employed [16]. The model is able to reproduce the precise geometry of the MgB_2 wire and incorporates highly non-linear characteristics of the materials composing the cable, such as non-linear magnetic permeability for nickel and monel and a power-law electrical resistivity for the superconductor. These non-linearities, as well as the geometry of the cable, which will be discretized at the level of the individual filaments, make the numerical simulations challenging.

IV. DEMO 5 PARTNERS AND THEIR ROLES

DEMO 5 is coordinated by Nexans France and comprises ten partners from five countries, bringing together industry (Columbus, Nexans), research organizations (CERN, IASS, KIT, RSE), universities (ESPCI ParisTech, TU Dresden, TU Madrid) and transmission operators (RTE).

Among the industrial partners, Columbus is responsible for the MgB_2 wire fabrication, whereas Nexans will be designing, assembling and testing the cable system, as described in the previous sections.

CERN will optimize the wires and the cable conductor for the application to power transmission in close cooperation with Columbus, for the wire, and RTE, for the cable, and will characterize the electrical performance of the wire and of the cable operated at currents of up to 20 kA.

IASS Potsdam is involved in the scientific coordination of the R&D work package, together with Nexans France who is in charge of the technical coordination. In the second half of the project, IASS will also have a leading role in the dissemination activities for the demonstration results.

KIT will analyze the electromagnetic behavior of the MgB_2 cable conductor, especially with respect to transient events, as presented in Section III.

RSE will contribute to the design and development of the 10 kA hybrid current leads and will be supporting other partners in the design, manufacturing and testing of termination prototypes with the aim of ensuring reduced losses in the system and lowering the impact on the cooling system.

ESPCI ParisTech will test the HV insulation of the cable under nominal conditions, i.e., under high electric stress and hydrostatic pressure in a cryogenic environment.

TU Dresden is responsible for the conceptual design of the cooling system and for the proper design of the cryogenic envelope for the superconducting cable, including insulation and hydraulic design.

TU Madrid will study various aspects pertaining to availability, with a particular focus on the cooling system: fault analysis, detection mechanisms, and risk evaluation.

The French transmission operator RTE will investigate the grid integration of the MgB_2 demonstrator and will also carry out a socio-economic assessment of the proposed power transmission system.

V. CONCLUSION

Within the European project BEST PATHS, DEMO 5 aims to confirm the potential for HVDC bulk power transmission using cables made out of MgB_2 superconducting wires. Started less than a year ago, the project will be dedicated to R&D activities in the first two years, followed in the final two years by demonstration results of a full-scale cable system able to transfer up to 3.2 GW.

In recent months, MgB_2 wire designs have been proposed and produced for the initial cable tests. The first validation experiments to investigate their mechanical suitability for cabling operations have already been successfully carried out on industrial cabling machines. The upcoming activities include validating the cable conductor design by simulations of fault and transient conditions, optimizing the current lead concept, defining the He gas injection tube, as well as commissioning the cryogenic test bench for the HV insulation.

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