MVDC MgB_2 superconducting cables for hybrid power transmission

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ABSTRACT

Combining liquid hydrogen and superconducting cables presents a unique opportunity for a more decarbonized world. The European project SCARLET has been launched to demonstrate inter alia the feasibility of an MVDC hybrid system that distributes hydrogen and bulk electricity in the same infrastructure. Liquid hydrogen at 20 K is perfectly suited for cooling MgB_2 *compact cables that are superconducting below 39 K.*

After a short presentation of the project, designs of MVDC MgB_2 *cables systems capable of transmitting 1 GW are discussed. A type test and long-term testing will be conducted to demonstrate the maturity and safety of the system.*

KEYWORDS

MVDC cables, MgB_2 wires, superconductivity, liquid hydrogen, hybrid power transmission

INTRODUCTION

Hydrogen (H_2) is foreseen to be an important energy vector for a more decarbonized world. To get its full benefits, it should be distributed to end users such as power plants, energy-intensive industries or fuel cells in buildings or multimodal transportation centres. Liquefied H_2 is regarded as one of the safest ways for its bulk distribution. In fact, to reach half of the density of liquid hydrogen (LH_2) at atmospheric pressure, room-temperature gaseous hydrogen should be pressurized at 600 bar. Beyond the intrinsic hydrogen risks that must be managed, distribution at such high pressure could be the source of many other hazards. An efficient and safe solution for distribution of hydrogen is to deliver its high-density liquid phase at 20-25 K (-250°C) under low pressure (< 20 bar). Inserting an MVDC superconducting cable in the LH_2 pipeline network offers a unique way to benefit from an existing cryogenic pipe network and distribute simultaneously electricity and hydrogen. However, the MVDC cable should be very compact to have a minimum impact on the hydrogen distribution possibilities.

The Horizon Europe project SCARLET has recently been launched to develop MVDC superconducting cable systems in the gigawatt range to ease the injection of renewable energy in the future grid. Its overall scope is presented in a separate contribution at this conference. The project has a duration of 4.5 years and gathers 15 partners investigating different superconducting technologies.

One work package is specifically focussed on developing, manufacturing and testing a full-scale superconducting cable cooled with LH_2 that could deliver 1 GW. Table 1 summarizes the general specifications proposed for the cable system.

Parameters	
Electric power	500 MW per pole
Voltage class	25 kV
Operating DC current	20 kA
Cooling medium	- LH_2 for cooling the superconducting cable and the voltage insulation. - Delivery of H_2 to user from 200 kg/h to 10 t/h *(7 m^3/h-150 m^3/h)* up to 3 to 20 kilometres. - Stored LH_2 in the pipe from 350 to 800 kg/km (5-10 m^3/km) corresponding to stored energy from 11.6 – 26.4MWh/km
Heat load at cryogenic temperature	< 2 W/m at 20K
Current ripples	< 1% amplitude at a few kHz
Fault current	58 kA during 10 ms

Table 1: General characteristics of the MVDC cable in liquid hydrogen for the EU project SCARLET

To achieve the demonstration goals, the work is divided into 7 interdependent tasks, each of them focused on one of the key components of the superconducting cable:

- Cable conductor
- HV insulation in LH_2
- High-performance cryogenic envelope
- Terminations and joints
- Cooling and liquefaction machine
- Safety in LH_2
- Testing

This paper describes designs that have been envisioned for the project. It also gives some fundamentals of the technology.

SUPERCONDUCTING CONDUCTORS

MgB_2 wires

Discovered in early 2000, MgB_2 is a superconducting material below 39 K. It fits perfectly with the temperature of H_2 in its liquid phase from 18 K to 25 K. Commercially available MgB_2 wires have been developed using the *ex-situ* Powder-in-Tube technique [1]. Such wires have already been used for manufacturing busbars and power cables that operate at low, medium, or high voltage [2,3].

As they are made of abundant and low-cost materials (Mg, B, Ni alloys) associated with a high-yield process, MgB_2 wires are foreseen to be a key and low-cost technology for the sustainable electrical grids. They offer an attractive solution for extremely high direct-current distribution. Long ageing in LH_2 or cold gas H_2 has already been carried out and did not show any degradation of the superconducting properties. Moreover, MgB_2 wires can be produced in cylindrical shape which fits with the cabling technology. For an optimized and robust cable design, it should present the smallest possible diameter (i.e., below or close to 1.5 mm) and the highest possible critical current I_c. An important parameter for cabling is the critical bending radius (r_c), defined as the minimum bending radius that the wire can withstand without degradation of its superconducting performance. An adequate value of r_c prevents deterioration during handling or during the cabling and rewinding operations.

The wire topology selected for the SCARLET project is shown in Fig. 1 and its main properties are summarized in Table 2 and Fig. 2. This wire is designed with 36 MgB_2 filaments embedded in a Ni alloy matrix. During the last years, the current carrying capability of these wires has increased by more than 20%. Today a single wire with 1.33 mm outer diameter can transport – without any Joule loss – a current up to 800 A in 0.7 T at 20 K when keeping r_c below 100 mm. Note that the transported current is dependent on the magnetic field seen by the wire that could be its self-field or an external field. An optimisation of the cable conductor characteristics (diameter, distance between poles, etc) must be investigated. Notably, its current transport capacity is isotropic with respect to magnetic field, which eases the design phase.

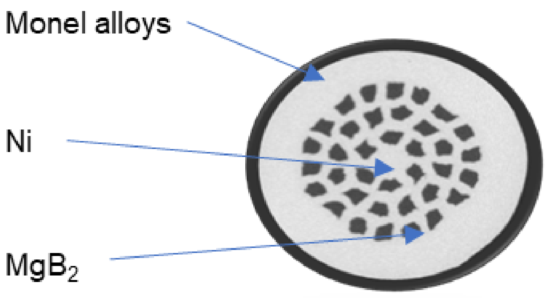

Fig. 1. Baseline wire proposed for SCARLET

Properties	
Diameter	1.33 mm
Constituent materials	Monel Nickel
Number of filaments	36
Filament diameter	40 µm
MgB_2 fraction	17%
I_c at 20 K & 1 T	650 +/- 25 A
I_c at 25 K & 0.8 T	460 +/- 20 A
r_c	80 mm

Table 2: Properties of the MgB_2 wire for the superconducting high-power cable in SCARLET

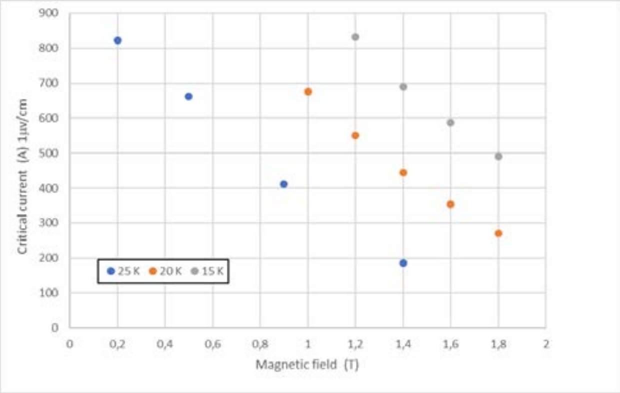

Fig 2: Critical current of the selected MgB_2 wire at different temperatures

As illustrated in Fig 2., MgB_2 wires can transport a significant current when maintained at a cryogenic temperature below 25 K. A precise and updated characterization of their mechanical properties, their critical current at different operating temperatures from 4.2 to 30 K and magnetic fields is carried out within SCARLET. The temperature can be maintained along the cable within a flexible standard cryo-envelope connected to a re-cooling system. The selected solution is discussed in Section V.

Cable Conductor

The use of MgB_2 wires offers a flexibility to design the cable conductor according to different approaches in terms of the current sustained during a fault and behaviour during the ensuing quench process. More precisely, two distinct approaches will be investigated within SCARLET: the “fault tolerant” and the “fault transparent”.

Fault-tolerant design

The fault-tolerant design entails the transition of the cable from the superconducting state to the normal resistive state during the fault. This design allows an over current during a limited time period with no damage to the conductor. However, the cable must be disconnected with fast switchgear from the grid and can be energized again only after the recovery of the operating temperature at 20 K. In SCARLET, the use of fast DC breakers is envisioned. They can open in less than 10 ms.

In the following, the characteristics of a single-stage fault-tolerant approach are presented. As illustrated in Fig. 3, the basic configuration is a cored rope cable, in which multiple MgB_2 strands are helically wound around a central, multi-strand copper core. When a fault occurs, this copper core is used to transport the excess current surpassing the critical value of the cable.

The selected design has 29 MgB_2 strands wound around a core with 37 copper strands of 1.6 mm diameter. This results in an external diameter of 15 mm for the cable conductor. During normal operation, each MgB_2 wire will carry 700 A @ 0.6 T for a total transported current of 20 kA. The cable critical current is estimated at 26 kA @ 0.7 T and 20 K which gives an operating current margin of approximately 30% enabling a cable operation up to a temperature of 23 K.

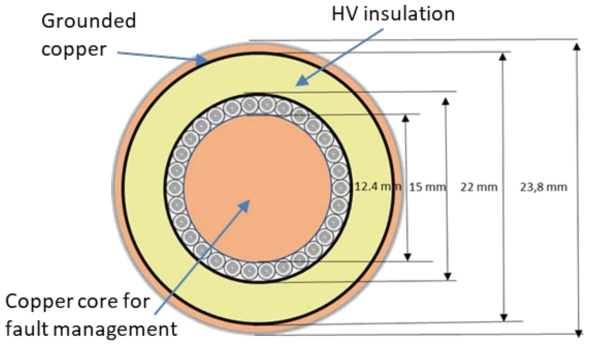

Fig 3. 500 MW MVDC cable cross section

A study of a double-stage fully transposed fault-tolerant cable design is also considered. The cable is made from identical sub-cables wound around a central support, and each sub-cable consists of MgB_2 wires twisted around a copper core. In such a design, the currents in each wire are balanced as each wire follows exactly the same path (same inductance). Although it needs 36 MgB_2 wires to transport 20 kA with similar margins, it offers a more compact design (outer cable conductor diameter of 13 mm) with a smaller section of copper. This offers a larger number of cable design possibilities than a single-stage process, which can make it attractive for various projects.

Fault-transparent design

The fault-transparent approach is enabled by the properties of the MgB_2 superconductor: high current and good stability at low cost. Thus, the high critical current of the MgB_2 wires allows for a cable design capable of withstanding the fault current without quenching, which in SCARLET requires a critical current of 60 kA for the cable. For this, only a double-stage cable conductor can be envisioned. In this case the fault current is passing through the cable. To accept such a peak current, 100 MgB_2 wires arranged in 8 to 12 petals are necessary. In this case the diameter of the cable conductor is larger but remains overall small at about 25 mm. We can expect a protected diameter of the cable of 34 mm.

Transient phenomena

The transient behaviour of the cable will be studied by modelling. To perform these investigations, numerical models solving the time-dependent Maxwell’s equations using finite-element methods will be developed. 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. A precise description of the transient profiles will be carried out within the project in another work package. This will consider different protection systems, fault locations, maximum power available at each end and converter technologies. The models can reproduce the precise geometry of the cable and incorporates highly non-linear characteristics of the materials composing the cable, such as non-linear magnetic permeability for nickel and monel alloy and a power-law electrical resistivity for the superconductor, as well as thermal conductivities. The most secure cable conductor design will be selected at the end.

ELECTRICAL INSULATION.

The MVDC MgB_2 cable system requires safe and simultaneous operation at both high current and medium voltage. As there is only limited literature on dielectric properties in LH_2, the voltage insulation for the cable will be fully characterized in the project. The dielectric properties are dependent both on the chosen material at 20 K and on the cooling medium, especially when LH_2 impregnates the insulation structure. Common synthetic extruded materials are not appropriate at such low temperatures since cracks may easily appear due to mechanical constraints and differential shrinkage, resulting in an irreversible degradation of the insulation. For cryogenic temperatures, it is chosen to build the electric insulation from lapped tapes. This lapping structure provides a sufficient mechanical flexibility thus preventing cracks. Within SCARLET two lapping tapes have been selected and will be tested: PolyPropylene Lapped Paper (PPLP) that has already demonstrated its ability to withstand high electrical fields in liquefied gas such as liquid nitrogen (LN_2) for DC HTS cables and Polyimide tapes that are commonly used for very low temperature voltage insulation down to 1.8 K. This material is expensive but has exceptionally high dielectric performance; for 25 kV class MVDC cable systems the required quantity remains limited, which makes this solution affordable.

As the breakdown value of a lapped insulation impregnated with LH_2 is not well documented, a characterization of these composite structures will be carried out. The existing literature on LH_2 performance indicates that the voltage breakdown level is slightly higher than in LN_2. Consequently, the first proposed design of the voltage insulation is based on similar rules as used for LN_2 [4], giving a conservative estimate of the insulation thickness.

With this approach for the single-stage fault-tolerant cable, an electric insulation layer with a thickness of 1.5 to 2.7 mm is sufficient for the insulation of a 25 kV class cable.

As illustrated in Fig. 3, a 500 MW MVDC cable has an overall diameter of only 22 to 24 mm including semiconducting layers, electrical copper shield and mechanical protection layers.

This design will be reviewed and validated after the dielectric testing campaigns in the project. Beside the voltage breakdown, space charges that could be trapped in the insulation layer will be characterized. This could be the case especially for polyimide lapping. A tentative characterisation of electrical charges created by the friction of the cooling fluid on the insulation layer will also be carried out.

As the number of test platforms in LH_2 are still limited, similar geometry samples will also be evaluated in LN_2 and gaseous He at 20 K to try to define rules of equivalence between the different impregnation media. This strategy will offer the possibility to prequalify the elements of the cable system in house before booking the final testing in LH_2 on a dedicated platform.

LH_2 AS COOLING MEDIUM AND ENERGY VECTOR

Any superconducting cable must be maintained at cryogenic temperature to transmit electricity without Joule losses. When inserted into a LH_2 pipeline network, the superconducting cable can be kept at a temperature below 25 K. However, to transmit sufficient LH_2 mass flow, the superconducting cable must be very compact. As shown above, an MVDC superconducting cable has a small overall diameter, especially when it is based on MgB_2 wires. In this case, an unrivalled compact design can be proposed.

The cable system is designed to provide LH_2 that could be adjusted by the pipe diameter. The amount required depends on the application. The mass flow rates required for some of the most common applications are given in Table 3. Most of these applications require H_2 and high electrical power at the same time, such as steel foundries that could be supplied by the MVDC hybrid superconducting cable.

The pipeline network can be built with corrugated cryogenic envelopes that are already compatible with LH_2 and are now available on the market. Within the SCARLET project, the thermal performance and pressure drop will be accurately measured and optimized if needed.

Already at this point, a first dual distribution system structure can be envisioned. As an example, a study of a 5 km long hybrid energy system has been carried out. The sketch of the cable cross section is shown in Fig. 4 and the key features of the system in Table 4.

Application	H_2 requirement	Electricity
Industry	10 t/h for a steel foundry	50 to 200 MW
Ships	200-300 m^3 LH_2 on board 2 to 3 t/h	50 to 100 MW
Ground	80 kg/truck 100 trucks 0.3 t/h 1000 trucks 3 t/h	150 kW per fast charge point 100 vehicles 15 MW

Table 3 Typical hydrogen and electricity requirements for different applications

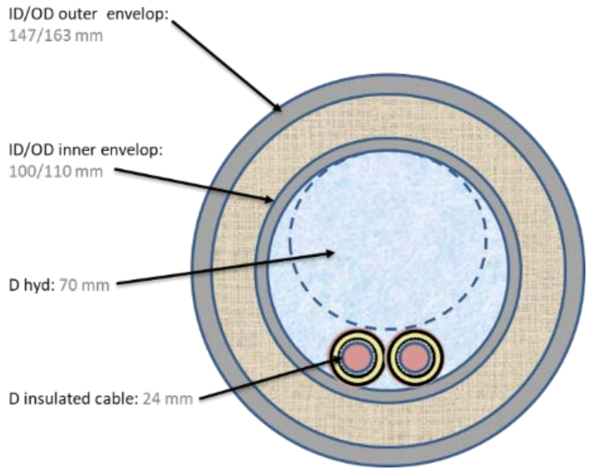

Fig 4. Cross section of the hybrid energy MVDC cable system in SCARLET

With this dimension of LH_2 pipe and cable, it is possible to deliver more than 2 t/h of hydrogen (0.56 kg/s), while keeping the cable core in the proper temperature and pressure conditions. The delivered hydrogen can store or supply a chemical energy of 80 MWh/h in addition to the 2 x 500 MW of electrical power. Depending on end-user requests, the H_2 supply can be adjusted by tuning the mass flow rate and/or using storage buffer tanks. It can also be increased when necessary (e.g., larger pipelines). The electrical power can be adjusted by reducing the transported current. The temperature rise is compatible with the requirements of MgB_2 wires. LH_2 distribution with a significant mass flow does not require any extra re-cooling stations along the cable. The pressure drop keeps the H_2 in liquid phase along the distribution pipe without any risk of generation of gas bubbles that would be expected to be detrimental to the electric insulation [5].

Parameters	Characteristics
Length	5 km
Bipolar cable	Up to 2x0.5 GW (2x20 kA,25 kV)
H_2 mass flow (t/h)	Up to 2.5
Temperature raise (K)	2
Pressure drop (Bar)	4

Table 4 Main characteristics of a hybrid energy MVDC system

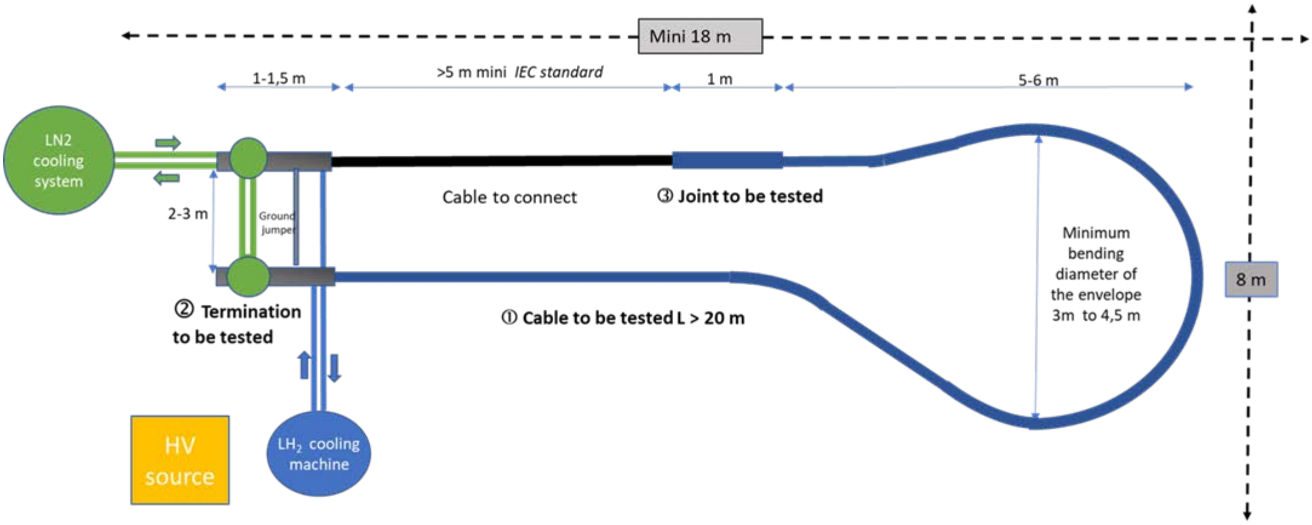

Fig. 5: Testing loop for the MVDC MgB_2 cable in LH_2 within SCARLET

Different business cases will be studied within SCARLET. Using the same infrastructure for gas and electricity distribution will save significant investment costs.

TESTING

A testing loop for a type test demonstrator operating at 20 kA and 25 kV will be built and installed in the second half of the project. As shown in Fig. 5, this will include two terminations, an electrical joint, a H_2 liquefaction unit, and a LH_2 buffer tank with its circulation pump. LN_2 will be also required on site for thermal shielding of the different cryostats and for reducing the heat load of the current leads at 20 K. The terminations and joint will be prepared according to the best designs and practices. Based on the experience acquired in previous projects [4], a 150 m long cable prototype with fault-tolerant architecture will be manufactured on an industrial cabling machine (see Fig.6) that can produce piece lengths of several kilometres.

The cable transport current will be tested by measuring critical currents on extracted wires and also directly by measurements of the cable.

The cable system will be designed according to the strictest recommendations and operated following precise safety instructions. The testing will not start until the safety issues associated to cryogenics, electricity and H_2 are totally cleared.

As no standards are yet existing for MVDC cable testing, the testing program will be inspired from last Cigré recommendations for testing DC cables and AC superconducting cables [6,7].

The type test carried out in LH_2 will include tests at 1.85 times the nominal voltage in both polarities, followed by lightning pulse tests. The exact thresholds and values chosen for the tests will be defined in the project and discussed with the end-users. This type test will be followed by 6-month cryogenic in-service tests.

Fig 6: Planetary cabling machine for the cable conductor

CONCLUSION

New superconducting MVDC cable technologies are investigated within the Horizon Europe SCARLET project. One of the demonstrators aims to combine a very compact superconducting cable with the distribution of LH_2, which would transfer two decarbonized energy vectors to end-users: electricity and hydrogen.

As they are superconducting below 39 K, MgB_2 wires are a perfect fit for the LH_2 temperature at 18-25 K.

Based on the experience acquired by the consortium in previous projects, a very compact MgB_2 cable can be industrially produced. Both fault-tolerant and fault-transparent cable designs will be investigated. The transient phenomena will be validated by modelling according to precise profiles defined in the project. In both cases, the cable remains very compact keeping a large channel for H_2 transmission.

Sharing the same infrastructure to distribute both H_2 and electricity is expected to decrease investment costs. As the H_2 is foreseen to be liquefied for its distribution, only limited extra cost for cryogenics is required to add the functionality of electricity distribution to the system.

As an example, the cross section of a bipolar cable system has been proposed that can distribute a large mass flow up to 2,5 t/h of H_2 fitting with the requirements of multimodal transportation centres.

Beside the characterisation and the validation of LH_2 as an insulating medium, the type test and long-term testing will be important steps toward the preparation of safety standards of operation in H_2 and of recommendations for a superconducting MVDC electrical test standard.

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