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MgB_2-Based MVDC Superconducting Power Cable in Liquid Hydrogen for Hybrid Energy Distribution

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***Abstract*—The combination of liquid hydrogen and superconducting cables presents a unique opportunity to distribute both hydrogen and bulk electricity in the same infrastructure. In particular, liquid hydrogen around 20 K is ideally suited for cooling the MgB_2 superconductor, resulting in a compact power cable that also leaves sufficient place for the hydrogen flow. Such a hybrid system operating in the MVDC range at 25 kV and 20 kA constitutes one of the main goals of the European project SCARLET. After a description of the rationale and benefits of the electricity – hydrogen system, various possible applications and a first distribution system are presented. Furthermore, the different cable components already designed are discussed along with the research challenges and general strategy for the development.**

***Index Terms*—**MVDC cables, MgB_2 wires, superconductivity, liquid hydrogen, hybrid power transmission

I. INTRODUCTION

HYDROGEN (H_2) is considered a promising energy vector for a more decarbonized future world and has become a key element of the EU Green Deal [1]. To get its full benefits, H_2 should be efficiently distributed to end users such as power plants, energy-intensive industries or fuel cells in buildings or multimodal transportation centers.

A safe and efficient solution for distributing large quantities of H_2 is to use its liquid phase at a temperature of 20-25 K (- 250°C) and at pressures below 20 bar, taking advantage of its high density. In fact, to reach half of the density of liquid hydrogen (LH_2), room-temperature gaseous hydrogen would need to be pressurized at over 600 bar, which would pose severe chemical risks and be hazardous for its distribution.

Inserting a very compact medium-voltage direct-current (MVDC) superconducting cable in an LH_2 pipeline offers a unique solution to simultaneously distribute the two energy vectors electricity and hydrogen. This opens interesting business opportunities with added values for the power grids, especially for transportation systems and energy-intensive metallurgical industries, where both electrical and chemical energy supplies are required. The idea was initially proposed by Grant [2] and a proof of concept at 2.5 kA and 20 kV was given by Vysotsky et al. [3]. The recent worldwide attention to green hydrogen has rekindled interest in this topic [4, 5].

Such an electricity – hydrogen dual distribution system will be developed in the European project SCARLET, which started in September 2022. The project has a duration of 4.5 years and gathers 15 partners who will develop onshore and offshore MVDC superconducting cable systems in the gigawatt range [6]. Its overall scope is presented in [7].

One of the main goals in SCARLET is to develop, manufacture and test a 500 MW DC monopolar cable system (1 GW in bipolar design) transferring 20 kA at 25 kV, while distributing H_2 in its liquid phase. Table I summarizes the general specifications of this MVDC cable system, which is the first demonstration of a hybrid energy system at the gigawatt level.

To achieve these ambitious demonstration goals, the work is divided into seven interdependent tasks, each focusing on one of the key components of the superconducting cable:

- Cable conductor
- High-voltage insulation in LH_2
- High-performance cryogenic envelope

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- Terminations and joints
- Cooling and circulation machine
- Safety in LH_2
- Testing

After explaining the rationale of the dual distribution system, this paper describes the possible designs that are envisioned for the cable system.

TABLE I
GENERAL CHARACTERISTICS OF THE MVDC CABLE IN LH_2 DEVELOPED IN SCARLET

Parameters	
Electric power	500 MW per pole
Voltage class	25 kV
Superconducting material	MgB_2 wires
Cable arrangement options	2 separated poles, 2 poles in one cryostat and coaxial cable
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 20 kilometers.
Heat load at LH_2 temperature	< 2 W/m at 20 K
Current ripples	<< 0.1% amplitude at a few kHz
Fault current	58 kA during 10 ms (worst case)

II. LH_2 AS COOLING MEDIUM AND ENERGY VECTOR

Any superconducting cable must be maintained at cryogenic temperature to transmit electricity without Joule losses. In an LH_2 pipeline network, the outlet temperature, and hence a superconducting cable inserted in the pipeline, can be kept below 25 K, a temperature very well suited for the MgB_2 material. To guarantee sufficient LH_2 mass flow, the superconducting cable must be very compact to not adversely impact the transfer of fluid. The main advantage of using an MVDC superconducting cable is its small cross-section, especially when the conductor is based on MgB_2 wires.

H_2 is foreseen as a sustainable way to store electricity produced in excess, ideally providing 120 MJ/kg. This value does not include the yield of transformation to electricity or mechanical energy. The energy required to generate and liquefy H_2 should also be considered in the business case analysis but is out of the scope of this paper.

Table II indicates that LH_2 is also an efficient cooling medium due to its high specific heat that partially compensates for its lower density compared to liquid nitrogen (LN_2). Massive LH_2 flow over long distances even with significant changes in elevation is possible with a limited pressure drop thanks to its low density and viscosity.

Unlike the case of LN_2 or gaseous He cooled cables, the LH_2 coolant is a significant resource, which generates revenues when delivered to customers, reimbursing the cryogenic system costs. The pipeline network can be built by corrugated cryogenic envelopes that are already compatible with LH_2 and are available on the market. The thermal performance and

TABLE II
PHYSICAL PROPERTIES OF LH_2, GASEOUS H_2 AND LN_2 AT 0.5 MPA [8]

Property	**Hydrogen**		**Nitrogen**
	Liquid 20 K	Gaseous 300 K	Liquid 70 K
Density (kg/m^3)	72	0.4	839
Cp (J/kg K)	9470	14320	2011
Viscosity (µPa s)	13.2	8.9	225
Solidif. Temp. (K)	13.9		63
Boiling Temp. (K)	27.2		94

pressure drop will be accurately measured within SCARLET and optimized, if needed.

The applications that could benefit from such an MVDC hybrid superconducting cable require both H_2 and high electrical power at the same time, for instance energy-intensive industries and green transportation systems. The hydrogen mass flow rates and electrical power for some of the identified applications are given in Table III. These values come from discussions with relevant stakeholders and practitioners that require the combined use of hydrogen and high electrical powers.

TABLE III
TYPICAL HYDROGEN AND ELECTRICITY REQUIREMENTS FOR DIFFERENT APPLICATIONS

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 transportation	80 kg/truck 100 trucks 0.3 t/h 1000 trucks 3 t/h	150 kW per fast charge point 100 vehicles 15 MW

As an example, the study of a 5 km long hybrid energy distribution system has been carried out. A sketch of the system cross section is shown in Fig. 1, illustrating two 500 MW poles in the selected cryogenic envelope. The key features of the system are given in Table IV, and the detailed structure of a pole in Fig. 2. Using these parameters for the LH_2 pipe and the cable, it is possible to deliver more than 2 t/h of hydrogen (0.56 kg/s), while keeping the cable in the temperature and pressure range suitable for the operation of the MgB_2 superconductor. The delivered hydrogen can store or supply a chemical energy of 60 MWh/h in addition to the 2 x 500 MW of electrical power.

Depending on end-user requirements, the H_2 supply can be adjusted by tuning the mass flow rate and/or using storage buffer tanks. For higher LH_2 transfer rate requirements, larger pipeline cross-sections are available. The electrical power can be adjusted by reducing the transported current. The temperature rise is compatible with the requirements of MgB_2 wires. For very long links, LH_2 distribution with a significant mass flow does only require a limited number of re-cooling stations along the cable (at distances > 20 km for a delivery of 2 t/h). The pressure drop keeps the H_2 in liquid phase along the distribution line without any risk of gas bubble generation that is expected to be detrimental to the electric insulation [9].

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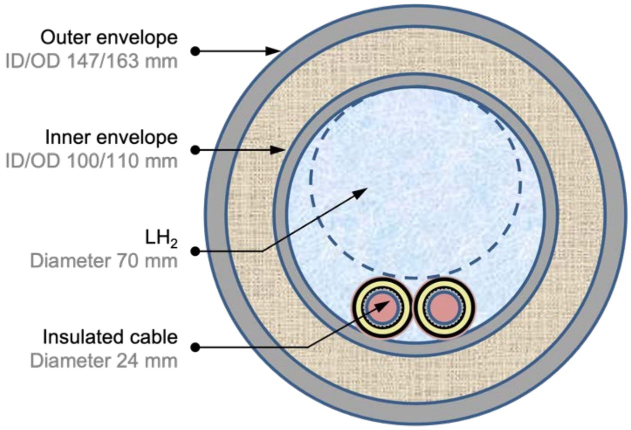

Fig 1. Cross section of the hybrid energy system consisting of 2 x 500 MW MVDC cables and LH_2 distribution.

TABLE IV
MAIN CHARACTERISTICS OF THE INVESTIGATED HYBRID ENERGY MVDC SYSTEM

Parameters	
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 rise (K)	2.5
Pressure drop (bar)	1.3

III. MgB_2 WIRES

The MgB_2 material is superconducting below 39 K and starts becoming usable for cable applications below 30 K, which fits well with the temperature of H_2 in its liquid phase from 18 K to 30 K. Commercially available MgB_2 wires are developed using the *ex-situ* Powder-in-Tube technique [10]. Such wires have already been used for manufacturing busbars and power cables that operate at low, medium, or high voltage.

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 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. In addition, the MgB_2 material can be produced in the form of round wires, which are suitable for cabling. Although they are based on the non-ductile MgB_2 compound, their composite structure gives them high mechanical strength and flexibility compatible with most machines and wiring processes.

The main properties of the wire selected for SCARLET are summarized in Table V. 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 900 A in 0.7 T at 20 K. More information on the MgB_2 wires is given in [11].

Today, MgB_2 wires are mostly used at temperatures below 25 K. However, there is ongoing work to increase the operation temperature. A precise and updated characterization of their mechanical properties, their critical current at different operating temperatures from 4.2 to 30 K in various magnetic fields is currently carried out within SCARLET.

TABLE V
PROPERTIES OF THE MgB_2 WIRE FOR THE SUPERCONDUCTING HIGH-POWER CABLE IN SCARLET

Properties	
Diameter	1.33 mm
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

IV. CABLE CONDUCTOR

The use of MgB_2 wires offers great freedom in designing the cable conductor especially in terms of management of high currents during a fault and the behavior during the ensuing quench process. The selected approach has a major impact on the development of the cable conductor. Based on the first grid model developed in SCARLET, it has been found that the fault current could reach 58 kA in the worst-case scenario. Two approaches will be investigated in the project: the fault-tolerant and fault-transparent designs. Here we focus on the first one, as the latter is not yet finalized and will be reported later.

The fault-tolerant design entails a controlled transition of the cable from the superconducting state to the normal resistive state during the fault. This design allows for an overcurrent during a limited time without damage to the conductor and its insulation. However, the cable must be disconnected from the grid with fast switchgear and can be energized again only after the recovery of the operating temperature at around 20 K. In SCARLET, DC breakers will be used, which can open in less than 10 ms [12]. During this time, the copper core of the cable conductor acts as a low-resistance electrical shunt protecting the superconducting wires. Recently developed models [13] will be used to estimate the temperature reached in the different cable components including the electrical grounded layer and the cryostat, to verify that there is no risk for damage.

As illustrated in Fig. 2, the basic configuration is a cored flexible rope conductor, in which multiple MgB_2 strands are helically wound around a central, multi-strand copper core. Similar cable conductors have already been manufactured in various projects validating this cabling concept [14,15].

More concretely, the proposed cable conductor has 29 MgB_2 strands wound around a core with 37 copper strands of 1.6 mm diameter, resulting in an external diameter of 15 mm. During normal operation, each MgB_2 wire will transmit 700 A in the self-field of the cable (0.6 T) for a total transported current of 20 kA. The cable critical current is estimated to be 26 kA at 20 K, which gives an operating current margin of approximately 30% enabling a cable operation up to a temperature of 25 K. This is acceptable for most of the applications envisaged.

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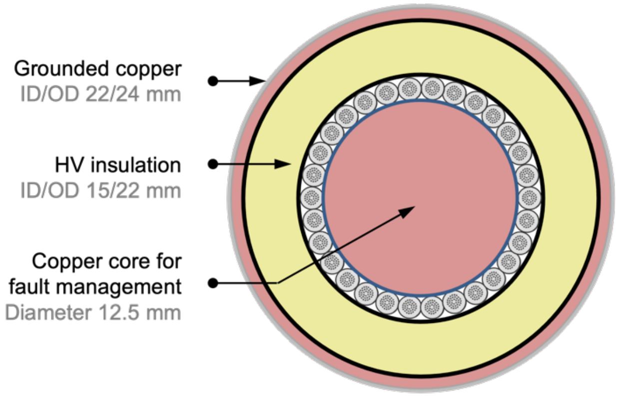

Fig 2. Cross section of the proposed MVDC cable pole for 500 MW electricity distribution presented in Fig, 1. The 29 MgB_2 wires form the outer layer of the cable conductor, wound around the central copper core.

V. Electrical Insulation

The MgB_2-based MVDC 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, different voltage insulation materials will be characterized. The dielectric properties depend both on the material (at 20 K) and on the cooling medium, in this case the LH_2-impregnated insulation structure.

The electric insulation consists of lapped tapes to provide sufficient mechanical flexibility. Three tape materials will be investigated and tested: two PolyPropylene Lapped Paper (PPLP) that have already demonstrated their ability to withstand high electric fields in LN_2 [16], and one polyimide tape that is commonly used for voltage insulation at very low cryogenic temperatures.

The first proposed design of the voltage insulation is based on similar rules as used for LN_2 [17], giving a conservative (large) estimate of the insulation thickness. As a result, an electric insulation layer with a thickness from 1.5 to 2.7 mm is anticipated to be sufficient for the insulation of a 25 kV class cable, thus keeping the power cable very compact. For additional safety, a grounded electric shield is added as an outermost layer around the cable insulation.

As illustrated in Fig. 2, the power cable has an overall diameter of only 24 mm including the electrical copper shield and mechanical protection layers. This design will be reviewed and validated after the dielectric testing campaigns and the fault modelling have been performed. In addition to voltage breakdown, space charges that could be trapped in the insulation layers will be characterized. This could be the case particularly for polyimide lapping. A tentative characterization 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 is still limited, evaluation in LN_2 and gaseous He at 20 K will be conducted to define the equivalence between the different impregnation media. This strategy will offer the possibility to prequalify the elements of the cable system before performing the final testing in LH_2 on a dedicated platform.

VI. Testing

Finally, a test loop for a type test demonstrator operating at 20 kA and 25 kV will be built. The test loop will include two terminations, an electrical joint and an LH_2 buffer tank with its circulation pump. The terminations and joint will be prepared according to the best designs and practices. Based on the experience acquired in previous projects [17], a 150 m long cable prototype will be manufactured on industrial cabling and insulation machines that can produce piece lengths of several kilometers.

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 the latest Cigré recommendations for testing DC cables and the recent standard for AC superconducting power cables [18,19].

To demonstrate the maturity, safety and reliability of the system, the type test will be followed by the 6-month operation in the field.

VII. Conclusion

One of the demonstrators in the SCARLET project aims to combine a very compact MVDC superconducting cable with the distribution of LH_2, which would transfer two decarbonized energy vectors to end users: electricity and hydrogen. A full MgB_2-based cable system including two terminations and a joint will be designed, industrially produced, and tested. Apart from characterizing and validating LH_2 as an insulating medium, the type test and long-term testing will be important steps toward the preparation of safety standards for operation in H_2 and of recommendations for a superconducting MVDC electrical test standard.

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