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SCARLET – A European Effort to Develop HTS and MgB_2 Based MVDC Cables

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***Abstract*—Superconducting cables have been proven in a variety of pilot projects and utility installations, demonstrating several of their advantages, including compact size and low energy losses, which can make the technology economically attractive for certain applications. It is clear though that different applications impose different requirements and challenges, but also opportunities for the cables. An interesting application is high-power DC transfer at medium voltage (MVDC). The high-current capability of the superconductor allows for a reduction in voltage while maintaining or increasing the power transfer level. In this way, one MVDC superconducting cable can replace one or more conventional high-voltage DC cables. In the European project SCARLET (Superconducting cables for sustainable energy transition), two types of MVDC cables will be developed, one based on HTS and one on MgB_2 materials. Additionally, protection requirements will be considered, including the development of a modular DC fault current limiter for 10 kA. A main motivation for the development is the elimination of costly high-voltage converter stations when going from high to medium voltage, e.g., for offshore wind power plants. Another feature is the combined hydrogen and electricity transmission from generation sites to industry or mobility end users. This paper describes the superconducting MVDC cable concept as well as the main challenges and research needed to develop and type test the cables.**

***Index Terms*—Cables, fault current limiters, liquid hydrogen, MVDC, superconductivity.**

I. INTRODUCTION

SUPERCONDUCTING cables have reached performance levels positioning them at the doorstep for commercial utilization. At the same time, new needs arise with the ongoing energy transition. For instance, power generation in remote areas requires efficient power export, and liquid hydrogen (LH_2) pipeline systems are foreseen, which should be combined with electricity transmission. Superconducting cables have the potential to contribute to realizing the energy transition in these areas in a cost-effective way.

More than 20 pilots of high-temperature superconducting (HTS) cables, both DC and AC, have been installed and tested around the world since 2000. An overview of HTS cable projects is given in [1]. The aim of all these pilots has been to validate the feasibility of the manufacturing, as well as the performances of the cable and its accessories (terminations, joints, thermal shrinkage compensation) for the different use cases. These projects have convincingly demonstrated that HTS systems of a few kilometers are feasible and can be commercialized for a very wide range of parameters.

Of these pilots, one may particularly mention a few. A district of the German city of Essen has been energized for more than seven years without any interruption or reported problems, using a kilometer-long AC superconducting cable in the AmpaCity project [2]. Before AmpaCity, the world's first installation of a superconducting cable in a live grid at transmission voltages was carried out on Long Island in the LIPA project, serving the equivalent of 300 000 homes [3]. The COMED project in Chicago ultimately aims at increasing the resilience of the business district by connecting three substations with a 62 MW link (12 kVAC / 3 kA) using YBCO tapes [4]. The major benefits for the customers are a reduction in both land acquisition and the disruptive impact of installation work. At the Ishikari site in Japan, a first superconducting medium-voltage DC, MVDC, cable (20 kV, 5 kA, 100 MW,

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500 m) was tested, followed by a second cable (20 kV, 2.5 kA, 50 MW, 1000 m). These bipolar coaxial cables were based on Bi2223 tapes and operated at 70 K [5].

Currently ongoing projects include SuperLink in Munich (500 MW, 110 kV, 12 km) [6] and SuperRail (1.5 kV, 3.5 kA, 80 m) at the Montparnasse railway station in Paris [7], both increasing the power transfer in existing ducts and avoiding costly creation of new rights of way.

For MgB_2-based cables, the most important project was the EU-funded Best Paths, validating high-voltage DC (HVDC) superconducting links and culminating with the first demonstration of a 3-gigawatt-class superconducting cable system operating at 320 kV and 10 kA [8]. Furthermore, the combination of hydrogen transport and MgB_2 cables was proposed twenty years ago [9] and demonstrated in a proof of concept in 2013 [10].

In this article, we discuss the development of MVDC superconducting cable systems in the framework of the European project SCARLET.

II. THE SCARLET PROJECT

SCARLET (Superconducting cables for sustainable energy transition) comprises 14 partners and is driven by the idea of utilizing the high current capability of superconducting cables to go from HVDC to MVDC for the same level of transmitted power [11]. The objective is to develop and industrially manufacture superconducting cable systems at the gigawatt level, bringing them to the last qualification step before commercialization.

The project started in September 2022 and has a duration of four and a half years. The main working areas are illustrated in Fig. 1. Onshore HTS and MgB_2 cables will be developed and demonstrated, whereas reinforced cryostats will be developed and tested for offshore cables. The system protection activities include the demonstration of a resistive superconducting fault current limiter module.

In addition to the demonstrators, system architectures will be designed to utilize the capabilities of the cables, and techno-economic studies will be performed. Also, activities will contribute to the work of including MVDC superconducting cables in the standardization framework.

III. HTS CABLES

In SCARLET, studies will be performed for onshore and offshore HTS MVDC cable systems to develop and optimize components required for the large-scale deployment of these technologies.

For onshore solutions, the focus will be on modular designs for cables and accessories, which would ease the deployment of multi-kilometer systems. In this respect, the behavior of MVDC cables during specific transient electrical phenomena will be simulated to enhance the understanding of the integration of the HTS cable system in the grid. Also, long-length systems require very efficient cable cryostats to maintain the low temperature at a low cost along the entire cable. A dedicated study will be performed on the loss reduction for the flexible cryostats surrounding the superconducting cable core and the cryogenic fluid. Finally, the cooling system is still a limiting component for the deployment of long-length HTS systems, and an optimization study dedicated to their reliability, maintenance, footprint, and integration into modular HTS cable systems, will be performed.

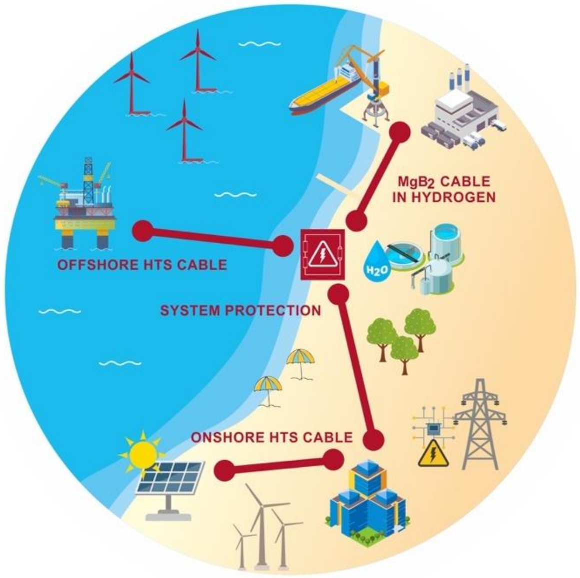

Fig. 1. Superconducting cables investigated in SCARLET.

Three potential cable structures have been identified for HTS MVDC applications and will be studied further in simulations to determine their benefits in a complete onshore or offshore system. These structures could be used in 1 or 2 GW applications at voltage levels of 50 and 100 kVDC, respectively. Each of these structures is considered as a use case to be investigated in detail in SCARLET. The use cases set criteria on various parameters, e.g., on potential redundancy, quantity of HTS tapes required, requirement of additional cryogenic return line, and environmental impact of the system, which together determine the interest for the solutions.

The first cable structure consists of two separate monopole HTS DC cables at +50 kV and -50 kV carrying 10 kA, as illustrated in Fig. 2. This configuration allows for the injection of the cryogenic fluid in one cable and the return flow in the other. The two monopoles are quite compact. However, high electromagnetic fields around each pole will probably impose a technical distance between them for proper operation.

The second structure, shown in Fig. 3, includes two concentric poles with symmetric voltages at +50 kV and -50 kV in one HTS cable. The diameter of this cable is slightly larger

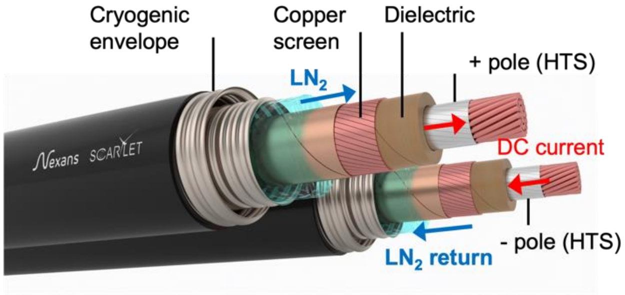

Fig. 2. MVDC power link at 1 GW based on two monopolar HTS cables of +50 kV and -50 kV carrying 10 kA each, with LN_2 circulation in one cable and return in the other.

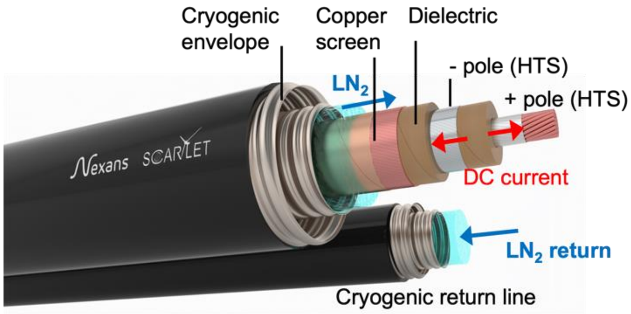

Fig. 3. MVDC power link at 1 GW comprising one HTS cable with two symmetric concentric poles at +50 kV and - 50 kV carrying 10 kA with the LN_2 return in a separate line.

than in the previous configuration, but the total cable system footprint is smaller. As the full current of 10 kA is flowing back through the outermost HTS phase, no external electromagnetic field is generated by this cable solution. However, the configuration requires a dedicated cryogenic return line for liquid nitrogen (LN_2) circulation.

The third cable structure is presented in Fig. 4 and consists of two separate cables with asymmetric monopoles: 0/+100 kV and 0/-100 kV. HTS tapes are also applied on the circumference outside the dielectric of both cables, called pole zero. Opposite currents flow in the cable core and in the pole zero. This configuration suppresses the external electromagnetic field. Additionally, it results in an interesting redundancy: the cables are completely independent and an electrical failure in one of them still allows the system to transmit half of the power. Hence, Fig. 4 presents a 2 GW solution, which will operate at 1 GW in a degraded mode (when one cable has an electrical failure). It should be noted that during a fault it is probably necessary to uncouple the ground points of the two cables at a substation to avoid grounding loops. This will be further studied. No return line is necessary for the cryogenic fluid in this configuration.

For each of these use cases, more detailed cable designs will be established and optimized by simulations, including e.g., dielectric thickness required, number and properties of HTS tapes, diameter of each layer, space required for the cryogenic fluid around the cable depending on the hydraulic circuit of the system. The impact of the detailed cable designs will then be included in complete system simulations to determine their applicability for MVDC onshore and offshore projects.

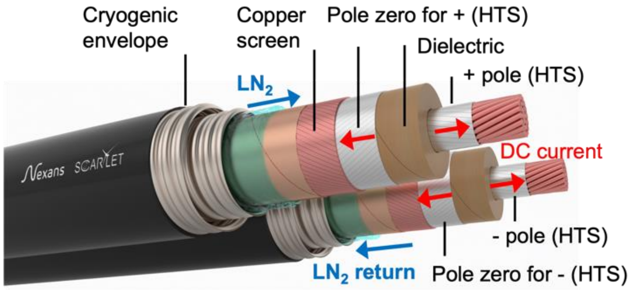

Fig. 4. MVDC power link at 2 GW comprising two HTS cables with two asymmetric concentric poles 0/+100 kV and 0/- 100 kV, with return current in the poles zero and LN_2 circulation in one pole and return in the other.

IV. OFFSHORE SUPERCONDUCTING CABLES

The potential of HTS MVDC cable systems for long-length bulk power transmission is unquestioned. However, demonstrators and systems validated in the grid have so far focused on onshore applications only. The onshore deployment may also be a prerequisite to convince technical communities and grid operators to go offshore with MVDC HTS technology. However, subsea MVDC cable systems present a potential impact even higher than onshore applications. The benefits of using submarine HTS DC cable systems are clearly linked to the intensive development of large wind farms located far offshore [12].

Most of the technology bricks available from onshore HTS cable system applications are directly transferable to submarine applications. Indeed, technologies developed for terminations, cooling systems, core of the superconducting cable immersed in LN_2, and related manufacturing processes are not really impacted by submarine constraints and remain mainly unchanged. Some preliminary studies emphasize that one of the main technical challenges for subsea applications is the adaptation of the cryogenic envelopes surrounding the superconducting cables and containing the pressurized LN_2 [13]. In marine environments, these cryogenic envelopes must withstand the outer water pressure and various dynamic mechanical loads which could be functional, environmental, or even accidental. Moreover, these envelopes, subjected to subsea constraints, should maintain the long-term robustness, efficiency, and quasi maintenance-free properties of the thermal insulation system.

Another challenge is the management of the cooling technology over very long offshore distances with the need for intermediate platforms. Our first thermal and hydraulic studies show that the cable systems shown in Figs. 2, 3 and 4 can be cooled on one side with one cooling station for lengths of 20 to nearly 40 km, with the distance depending strongly on the sea depth and the choice of cable cryostat.

V. MGB_2-BASED MVDC SUPERCONDUCTING CABLE FOR HYBRID POWER DISTRIBUTION

In parallel with the work on HTS cables, SCARLET will develop LH_2-cooled MVDC cables based on the MgB_2 superconductor with a very similar technical approach as described in the previous sections. The technical details are presented in a dedicated paper [14]. Here we outline the main concept.

Hydrogen is an energy storage medium considered as key to achieving the decarbonization goals, while also providing independence and security of energy supply. An efficient solution for distributing large quantities of hydrogen is to use its liquid phase at a temperature of around 20 K and atmospheric pressure.

Inserting a very compact superconducting cable in an LH_2 pipeline offers a unique solution to simultaneously transmit the two energy vectors electricity and hydrogen, so-called hybrid or dual transmission. Hybrid transmission opens various business opportunities based on the placement of such a system in the power grids and hydrogen pipeline networks, especially for transportation systems and energy-intensive industries, where large quantities of both electrical energy and hydrogen are needed. As an example, Fig. 5 illustrates the use of such a hybrid system for a green port, with several applications presented in [14].

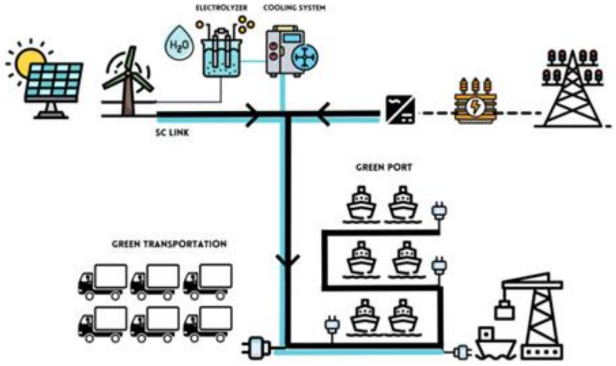

Fig. 5. Schematic diagram of hybrid power supply for a green port.

At the LH_2 temperature of 20 K, commercial superconducting materials such as REBCO and MgB_2 are very efficient. In addition, using MgB_2 results in very compact MVDC cables that can be inserted in the LH_2 pipeline with only a marginal decrease in the hydrogen mass flow.

To demonstrate the readiness of such dual-transport systems, SCARLET will develop a 500 MW DC monopolar cable system (1 GW in bipolar design) transferring 20 kA at 25 kV. The proposed diameter of the cable is approximately 25 mm including the 25 kV-class insulation. The cable size is well suited for pipelines with an LH_2 transport capacity of 2-10 t/h, which is identified as appropriate for ports and industrial demand.

Apart from demonstrating the feasibility and maturity of all the key components of such a superconducting cable, the system will be tested under the strictest consideration of all the safety requirements for operation in LH_2. Type testing will be followed by operation in the field for a 6-month period at the very end of the project.

VI. SYSTEM ARCHITECTURE AND PROTECTION

To utilize the MVDC superconducting cables, operating below ±100 kVDC at a typical transmitted power of 1 GW, the technical requirements of the electrical system in which the cable will be integrated must be studied.

Typically, present 1 GW converters are operated at high voltage (±320 kVDC and ±525 kVDC). SCARLET will propose a design for a 1 GW medium-voltage converter that can be the basic device for different applications, i.e., bulk offshore or onshore wind power export, interconnections of two electrical systems, power supply of large industrial or port areas.

One case of interest is the power export from large wind farms located far offshore, which today uses HVDC export cables and requires a large offshore conversion platform. Here, using an MVDC superconducting cable instead of a conventional HVDC cable offers the possibility to suppress the conversion function of the offshore platform, while keeping only a switching platform as illustrated in Fig. 6. This approach will reduce the platform volume by at least 50%, resulting in a huge simplification and cost reduction. Notably, to accomplish this simplification, the conversion chain of the wind farm must be reviewed, to set the individual wind turbine output voltage to the appropriate DC level, which becomes possible at medium voltage.

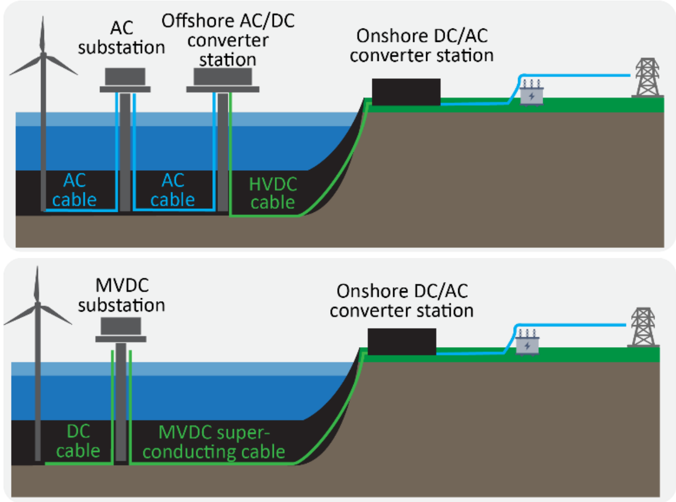

Fig. 6. Top: Today's solution for the export from large wind farms far offshore. Power is generated in AC and converted to HVDC on an offshore converter platform. Bottom: Solution with export through an MVDC superconducting cable, generating the power from each wind turbine in DC and eliminating the offshore converter platform.

The converter architecture proposed in SCARLET will offer new opportunities to maximize the continuity of service in case of faults in the converter itself or in one offshore cluster. A selective protection scheme will be elaborated combining the benefits of MVDC circuit breakers and a resistive superconducting fault current limiter (RSFCL). This protection principle will be applied to both HTS and MgB_2 cables.

The benefit of the RSFCL will be to relieve the superconducting cable from fault-current stresses and to be able to re-establish the power flow much quicker due to faster regeneration time compared to the superconducting cable alone. An RSFCL module with nominal current of 10 kA will be designed, produced, and tested within the project.

To verify the soundness of the protection strategy and the proper design of the superconducting cable and protection devices, a full model will be built into an electro-magnetic transient software and a variety of faults and system configurations will be simulated. This full model will also incorporate thermo-electrical models of the superconducting cable as well as the RSFCL, specifically developed for the project. Parts of this work are described in [15].

VII. CONCLUSION

The SCARLET project will develop and test two types of MVDC superconducting cables, one based on HTS tapes and one on MgB_2 wires. The developed cables will be studied for multiple uses, including offshore applications and combined electricity and LH_2 transport. To maximize the overall benefits of the cables, the system architecture will be thoroughly studied, and a protection scheme will be developed, including a resistive superconducting fault current limiter.

REFERENCES

[1] M. Yazdani-Asrami, S. Seyyedbarzegar, A. Sadeghi, W. T. B. de Sousa, and D. Kottonau, “High temperature superconducting cables and their performance against short circuit faults: current development, challenges, solutions, and future trends”, Supercond. Sci. Technol., vol. 35, 083002, 2022.

[2] 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.

[3] F. Schmidt, J. Maguire, T. Welsh, and S. Bratt, “Operation Experience and further Development of a High-Temperature Superconducting Power Cable in the Long Island Power Authority Grid”, Phys. Proc., vol. 36, pp. 1137-1144, 2012.

[4] D. Brotzman and J. Maguire, “Chicago Superconductor Cable Project and Vision for the Technology”, Presented at 32nd International Symposium on Superconductivity, Kyoto, Japan, December 2019.

[5] N. Chikumoto *et al.*, “Second Cooling Test of 100-m Superconducting DC Cable System in Ishikari”, IEEE Trans. Appl. Supercond., vol. 28, 5401005, June 2018.

[6] W. T. B. de Sousa, “SuperLink - Impacts of a Superconducting Power Cable in a 110kV Network”, presented at EUCAS2023, Bologna, Italy, 3-7 September 2023.

[7] A. Allais *et al.*, “SuperRail - World-first HTS cable to be installed on a railway network in France”, IEEE Trans. Appl. Supercond., submitted. Presented at EUCAS2023, Bologna, Italy, 3-7 September 2023.

[8] 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 Electr. Insul. Mag., vol. 36, pp 30–40, 2020.

[9] P. M. Grant, “The supercable: dual delivery of hydrogen and electric power” IEEE PES Power Systems Conference and Exposition, 2004., New York, NY, USA, pp. 1745-1749, 2004.

[10] V. S. Vysotsky et al., “Hybrid Energy Transfer Line With Liquid Hydrogen and Superconducting MgB_2 Cable—First Experimental Proof of Concept”, IEEE Trans. Appl. Supercond., vol. 23, no. 3, 5400906, June 2013.

[11] Project website. [Online]. Available: https://scarlet-project.eu/. Accessed on: 25 Sep. 2023.

[12] M. Cullinane, F. Judge, M. O'Shea, K. Thandayutham, and J. Murphy, “Subsea superconductors: The future of offshore renewable energy transmission?”, Renew. Sustain. Energy Rev., vol. 156, 111943, March 2022.

[13] H. P. T. Pereira, V. N. Dinh, L. C. Trinh, and J. Murphy, “Modelling of superconducting cable systems for marine applications: SuperMarineOne Project Final Report” DOI: 10.5281/zenodo.5621301, October 29, 2021.

[14] C. E. Bruzek *et al.*, “MgB_2-Based MVDC Superconducting Power Cable in Liquid Hydrogen for Hybrid Energy Distribution”, IEEE Trans. Appl. Supercond., submitted. Presented at EUCAS2023, Bologna, Italy, 3-7 September 2023.

[15] C. Creusot *et al.*, “Superconducting Cable Modelling into Electro-Magnetic Transient Simulation Tool”, IEEE Trans. Appl. Supercond., submitted. Presented at EUCAS2023, Bologna, Italy, 3-7 September 2023.