Superconducting Cables for Europe's Energy Transition

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ABSTRACT

SCARLET, "Superconducting CAbles foR sustainabLe Energy Transition", is a new Horizon Europe project funded for a duration of 4.5 years. The goal of the project is to develop and industrially manufacture superconducting cable systems at the gigawatt level, bringing them all the way to the type test. SCARLET will be carried out by 15 partners in the fields of material sciences, cryogenics, energy systems and electrical engineering. This paper will give an overview of the main topics in SCARLET, highlighting the innovations and challenges.

KEYWORDS

superconductivity, MVDC cables, high-power transmission, gigawatt cables, HTS, MgB_2

INTRODUCTION

Due to their compact size and ability to transmit high electric powers with great efficiency and reduced environmental impact, superconducting cables represent a promising option for the upgrading and extension of the European grids. In particular, superconducting cables will enable more efficient and less costly power transmission from remote renewable electricity generation sites to busy consumption centres.

In the past decade, a growing number of projects related to superconducting cables of various lengths and capacities have been constructed or become operational worldwide [1,2]. A prominent example of a superconducting cable installed in the grid is the AmpaCity project in downtown Essen, Germany [3]. The 1 km long AC cable is based on high-temperature superconducting (HTS) materials and is cooled using liquid nitrogen, operating under a voltage of 10 kV and a current of 2.4 kA rms. The cable system energized a full district close to the city center and was in operation for more than 8 years.

The promise of superconducting cables for the future grid was recognized by the European Commission with the funding of the Best Paths project from 2014 to 2018. This project demonstrated a full-scale 3-GW-class DC superconducting cable system operating at 320 kV and 10 kA and meeting the requirements for grid integration [4].

The new Horizon Europe project SCARLET (acronym for "Superconducting cables for sustainable energy transition") builds on the previous development and demonstration work on high-power superconducting links, focusing on two main technologies and on the medium-voltage instead of high-voltage range. The project started in September 2022 and will run for 4.5 years with the aim of bringing the developed superconducting cable systems to the last qualification step before commercialization. The main demonstration topics in SCARLET and their complementarity within a transmission grid are depicted in Fig. 1. The application spectrum is quite broad and includes onshore HTS cables connecting land-based renewable generation sites to the grid, offshore HTS cables serving as export cables bringing the energy to the shore from offshore windfarms, and MgB_2 cables in combination with liquid hydrogen transport connecting renewable energy sources with ports, ground transport and industries in need of both electricity and hydrogen. In conjunction with the developed cables, the protection of the cable systems and the grid is also investigated in the project.

In the following, an overview of these main demonstration topics will be given, emphasizing the innovations and challenges ahead.

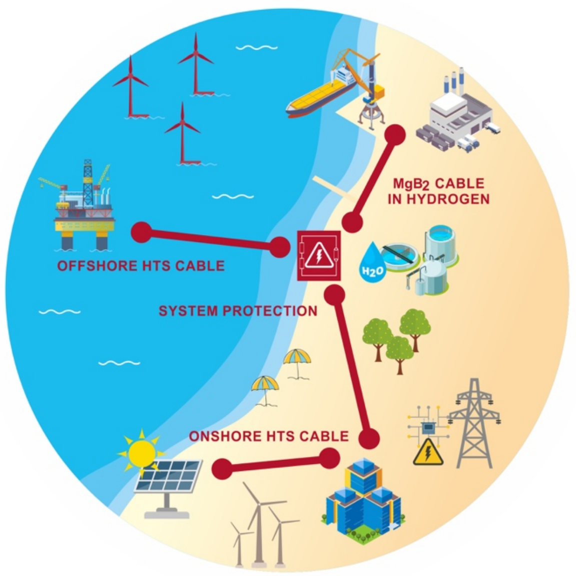

Fig. 1: Complementarity of the SCARLET demonstrators within a pan-European transmission network from remote renewable electricity production to high-load consumption centres

SCOPE AND STRUCTURE

SCARLET brings together 15 industry and research partners from 7 countries, spanning the fields of material sciences, cryogenics, energy systems and electrical engineering. The project is coordinated by SINTEF Energy Research and additionally includes the following partners: Absolut System, ASG Superconductors, ESPCI, IEE Slovak Academy of Sciences, Nexans France, Nexans Germany, RIFS Potsdam, RINA Consulting, RSE, SuperGrid Institute, SuperNode, University of Bologna, Vision Electric Super Conductors, and WavEC.

The main development and demonstration topics in SCARLET are:

- Development, industrial manufacturing, type test, and demonstration of full-scale high-temperature superconducting cables cooled with liquid nitrogen for a bipolar 1 GW link (±50 kV/10 kA)
- Design of offshore superconducting medium-voltage direct-current (MVDC) links cooled with liquid nitrogen for bipolar 1 GW power transfer (±50 kV/10 kA)
- Development, industrial manufacturing, type test, and demonstration of full-scale MgB_2-based superconducting cables cooled with liquid hydrogen for a bipolar 1 GW link (±25 kV/20 kA)
- Simulation of comprehensive electric system use cases, their protection requirements, and design and demonstration of a superconducting fault current limiter module able to handle a nominal current of 10 kADC.

The project is organized in seven work packages, as illustrated in Fig. 2. Apart from the three demonstrators and the work on submarine cables, there is a work package dedicated to economic evaluations and in-field integration studies as well as work packages for dissemination and coordination.

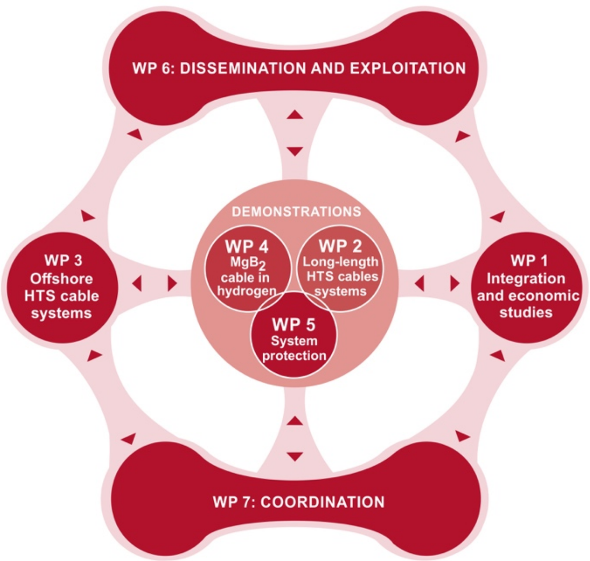

Fig. 2: Graphical representation of the SCARLET work packages and their interdependencies

All SCARLET technologies are designed for medium-voltage operation, enabled by the high-current capability of superconductors, which preserves an overall high transmission power otherwise only achievable at high voltage. The MVDC operation eliminates costly high-voltage converter stations and allows for significant overall cost reductions.

Techno-economic assessments will be performed for all technologies under consideration in SCARLET, to confirm their beneficial application areas and advance their exploitation paths. In the comparison between superconducting and conventional cable systems, a holistic approach will be applied considering, in addition to the cables themselves, the benefit of operation at lower voltages offered by superconductivity.

LONG-LENGTH HTS CABLE SYSTEMS

Due to their high power rating at MVDC, HTS cables are becoming very interesting for use at different locations in the grid, in particular for connecting renewable energy generation sites. Although there is only a limited number of HTS DC cables worldwide, most of the technical achievements in MVAC and HVAC HTS systems are directly transferable, especially the cable manufacturing process, the cooling system, cryogenic engineering and on-site installation processes.

In terms of length, the maximum demonstrated up to date for HTS DC systems is 2500 m [5] including several joints. And the maximum developed unitary length between two joints remains for the moment limited to about 500 m [6].

In terms of DC testing, a first step was carried out in Best Paths, which validated a superconducting cable and termination prototype developed for a DC class up to 320 kV [4]. The validation included DC voltage tests up to 592 kV (see Fig. 3) and the corresponding lightening and switching superimposed tests required for such HVDC voltage class. This HVDC validation reduces drastically the risk for the MVDC technology envisaged in SCARLET.

Fig. 3: Best Paths testing loop (cable and terminations) together with the 800 kV DC generator

In SCARLET, the focus will be on a modular design for an MVDC HTS-based cable and accessories which would ease the deployment of multi-kilometer systems. The behavior of the HTS MVDC cable during specific transient electrical phenomena will be simulated to have a better understanding for the grid integration of the system.

Long-length systems require a very efficient cable cryostat to maintain the cryogenic temperature over long distances. A dedicated study will therefore be performed on the reduction of losses for the flexible cryostats surrounding the superconducting cable core and the cryogenic fluid.

Finally, the cooling system is still a limiting parameter for the deployment of long-length superconducting systems and an optimization study will be performed regarding its reliability, maintenance, footprint and integration in the modular architecture of the HTS cable system.

The last part of the project will focus on the manufacturing and testing of a complete HTS MVDC cable system prototype, in order to push the technology readiness level to 8 and open the door to commercial deployment. This prototype will include the HTS MVDC superconducting cable designed during the project, its optimized flexible cryostat, two terminations, one joint and a dedicated cooling system. Dielectric, current and loss tests will be performed on the prototype to validate the technology and gather data to feed into future models simulating HTS MVDC in the grid.

OFFSHORE HTS CABLE SYSTEMS

SCARLET is the first publicly funded project with an offshore superconducting component, confirming the potential of superconductivity for offshore development, which is one of the basic pillars of the European Green Deal. Achieving subsea power transmission at high power capacities and low energy losses is paramount for the future of the offshore renewable energy sector. The submarine HTS cable systems developed in SCARLET will enable transmission of large amounts of power (>1 GW) at medium voltage (50-100 kVDC). This technology opens new possibilities for offshore renewable energy production and export using medium voltage along the energy conversion chain.

The main idea behind the MVDC operation of offshore cables is that it eliminates costly high-voltage converter stations, while keeping the same number of connecting cables. This simplification of the offshore connections leads to smaller and much less expensive equipment at offshore wind power farms and is schematically shown in Fig. 4.

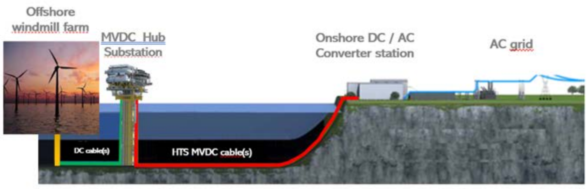

Fig. 4: Schematic illustration of the SCARLET solution for offshore wind connections using MVDC high-current superconducting cables

In an initial step, the most relevant use cases that crystallize the benefits of this technology will be selected and the main parameters of the corresponding cable systems will be specified. The use cases are chosen based on key parameters such as water depth, seabed geology, cable length, typical deployment methodologies, and are refined based on stakeholders' needs and requirements. For each use case, the cable system architectures will be presented and discussed with relevant industry asset owners and operators.

A techno-economic assessment will be carried out for each use case as part of the iterative process to ascertain optimal cable system architectures. This will include comparisons with reference scenarios resorting to commercially available offshore cables. Additionally, the environmental impacts and the life cycle of both commercial and SCARLET submarine cables will be assessed and compared.

Most of the technological building blocks available from onshore HTS cable systems are directly transferable to offshore applications. Indeed, technologies developed for terminations, cooling systems, superconducting cable conductor immerged in liquid nitrogen or related manufacturing processes are not really impacted by submarine constraints and would remain mainly unchanged. Some preliminary studies emphasize that one of the main technical challenges for subsea applications is related to the cryogenic envelopes surrounding the superconducting cables and containing the pressurized liquid nitrogen [7]. In a marine environment, these cryogenic envelopes have to withstand various mechanical dynamic loads which could be functional, environmental, or even unintended.

As the Technology Readiness Level is lower for offshore than for onshore systems, the SCARLET development work will focus on specific components which are affected by the marine environment:

- Designs of HTS cables up to 100 kilometer long and including a flexible cryostat reinforcement adapted to deep submarine constraints will be defined and optimized.
- The thermal shrinkage management, not directly transferable from the onshore technology, will require a specific study.
- Adapting the joint design to subsea constraints will also be necessary.
- Management of the cryogenic cooling over long distances and the necessity of intermediate platforms will be investigated.

A techno-economic assessment will be carried out for each use case identified in the project as part of the iterative process to ascertain optimal cable system architectures. This will include comparisons with reference scenarios resorting to commercially available offshore cables. Additionally, the environmental impacts and the life cycle of both commercial and SCARLET submarine cables will be assessed and compared.

MGB_2 CABLE IN LIQUID HYDROGEN

In addition to the HTS-based superconducting technology, MgB_2-based superconductors will also be investigated in SCARLET. This superconductor operating at 20 K was already validated for high-power electricity transfer in the Best Paths project [4].

In SCARLET, however, an MgB_2-based cable system will be demonstrated in liquid hydrogen instead of the gaseous helium used in Best Paths. The combination of MgB_2-based cables and liquid hydrogen in the same pipeline offers a unique opportunity to simultaneously transmit two independent energy vectors: electricity and hydrogen. Both of them are considered key to supporting the decarbonisation processes in Europe and worldwide. Distributing both a large quantity of hydrogen and electricity in the gigawatt range in the same infrastructure is particularly beneficial for green transportation systems and energy-intensive industries, where high amounts of both electrical and chemical energy are required.

As the overall scope of this demonstrator is presented in a separate contribution at this conference, only a brief summary is given here. In a nutshell, a complete set of components for this cable system will be designed, manufactured, assembled and tested. This includes the MgB_2 cable conductor, electrical insulation, cryogenic envelopes, terminations, field joint, and hydrogen liquefaction with its associated cooling system.

Although building on processes that are partly industrialized (see Fig. 5), the system design will need to take into consideration the safety requirements for operation in hydrogen. The cable design will also need to be easily adaptable to other requirements by the end users such as different operation currents or voltages.

The the testing of the cable system will be conducted on a dedicated platform (type test procedure) followed by long-term field testing to prove its reliability.

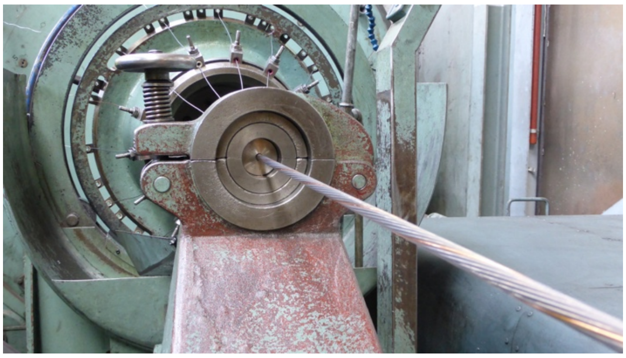

Fig. 5: Planetary cabling machine for the industrial manufacturing of the cable conductor

SYSTEM PROTECTION

The protection strategy of the system needs to not only ensure the safety of the superconducting cables and converters, but also maximize the availability of the power transmission. The scope of the system protection activities in SCARLET is therefore two-fold: on the one hand the DC system architectures and protection will be thoroughly investigated for the developed technologies, and on the other hand a module for a superconducting fault current limiter with 50 kVDC voltage rating and 10 kADC current rating will be demonstrated.

The fault current limiter is a key protection element and has to carry the same load current as the superconducting cable, i.e., at least 10 kADC for SCARLET. HVDC and MVDC circuit breakers have typically rated currents of 2 kADC, and no development has been carried out for higher currents. This was limited on the one hand by the trade-off between the very short opening time and moving mass of the mechanical switches and, on the other hand, by the on-state losses of power electronic components when used in the primary branch.

An alternative solution is to use a Resistive Superconducting Fault Current Limiter (RSFCL) in series with the SC cable, which limits the peak fault current with instantaneous reaction time, allowing for more time to interrupt the current. The RSFCL is used in combination with a DC circuit breaker, of the simplest and cheapest type. An RSFCL exploits the properties of superconducting materials to switch instantaneously from the almost perfectly conducting state to the resistive state based on the instantaneous current value. Hence, if the operating current exceeds a threshold value, the conductor becomes almost instantaneously resistive.

For the overall system protection, different conversion architectures will be reviewed for selected case studies. Based on the chosen system architecture and protection strategy, transient currents and voltages will be evaluated in order to specify the requirements for the superconducting cable and the different components of the protection system such as circuit breakers and fault-current limiters.

Based on these specifications, an RSFCL module operating at 3 to 6 kVDC and 10 kADC will be designed, manufactured, and tested during the project. To reach 50 kVDC, several identical modules need to be connected in series inside a cryostat. To achieve a nominal current of 10 kADC, it will be necessary to connect a high number of conductors in parallel inside one pancake-shaped coil within a module and then to further connect several such pancakes in parallel.

The RSFCL module will be demonstrated in subcooled liquid nitrogen inside an actual high-voltage size cryostat (see Fig. 6) and using a high-power testing platform to provide the DC fault current under the rated module voltage.

Fig. 6: High-voltage cryostat to be used for the demonstration tests of the RSFCL module

STANDARDIZATION ACTIVITIES

Beyond the interdisciplinary work inherent to such a complex project, there is also the intention to involve relevant practitioners at an early stage. Relevant stakeholders include manufacturers, offshore wind operators, TSOs, DSOs, IPPs, engineering companies, and international organisations. Their needs and perspectives as well as practical knowledge were already integrated into the project through the establishment of an Advisory Group. This will ensure that the developed technologies are relevant to a broad spectrum of end users.

In addition to involving stakeholders early on and incorporating their feedback throughout the project, there is a special focus on standardization activities. So far, no standard has been established for testing DC superconducting cables at either medium or high voltage. However, the testing of superconducting AC power cables and their accessories for rated voltages from 6 kV to 500 kV has been published as IEC standard 63075 in 2019. A starting point for addressing the DC requirements is provided in a Cigré brochure, which has recommendations for testing DC extruded cables operating at voltages up to 800 kV [8].

For the first HVDC superconducting cable system demonstrated in the EU project Best Paths [4], the testing was carried out based on the combination of these two established international practices. The HV testing experience gathered in Best Paths along with the further MV experience that will be gained in SCARLET should be used toward preparing a first set of recommendations for the MVDC and HVDC superconducting standards of the future.

As there is currently no working group dedicated to superconducting cables, it would be desirable to call such a group into life within the framework of Cigré, ideally involving both manufacturers and transmission system operators. A special focus should be set on testing MVDC superconducting cables, with the knowledge and insights from SCARLET being integrated into the working group. Ideally, the working group recommendations and proposed testing protocols could be applied and validated in the project, with the results fed back to the group. By the end of SCARLET, it may be possible to compile the recommendations into a Cigré report that could then be forwarded to IEC to prepare an international standard.

In addition to the standardisation activities, work towards certification is also foreseen with a particular focus on the liquid hydrogen cryogenic system for cooling a superconducting cable. Special attention will be paid to non-technical aspects that may pose limitations for market entry such as regulatory restrictions, and to solutions for overcoming these barriers. The outcome will be a roadmap to support policy makers/technical committees in developing specific technical norms for certification of the liquid hydrogen cryogenic system.

CONCLUSIONS

MVDC superconducting cables allow for high-power transmission with improved system efficiency and reduced environmental impact. Recently there has been growing interest in this technology, thanks to the high ampacity, compactness and grid simplification, especially for offshore applications. By bringing MVDC superconducting cables at the gigawatt level all the way to the type test, the EU project SCARLET will contribute to the improvement of their technology readiness level toward commercial availability.

Acknowledgments

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