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REVIEW

High voltage direct current transmission cables to help decarbonisation in Europe: Recent achievements and issues

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Abstract

High Voltage Direct Current (HVDC) underground and submarine cables constitute an essential technology for the long-distance transmission of renewable electrical power with low losses, thereby fostering decarbonisation. In the past 2 decades, all this yielded a quasi-exponential rise of HVDC cable systems installed worldwide, but has also made the working conditions of HVDC cables harsher. In this paper, the contribution of HVDC cables to decarbonisation is tackled, with particular reference to the situation in Europe, and a few simple calculations showing in general terms the quantitative contribution provided by HVDC cable systems to decarbonisation are given. Then, the major issues towards long-lasting and reliable HVDC cable systems are summarised briefly, focussing—for the sake of brevity—on the influence of the main HVDC cable technologies, of cable laying environment and of duty service. Some hints are also provided at the chances given by multiterminal HVDC systems.

1 | INTRODUCTION

Since the beginning of their history, the features of High Voltage Direct Current (HVDC) transmission systems have made this technology particularly attractive for certain applications, that is, long-distance bulk-power delivery, asynchronous interconnections, and long submarine cable links [1, 2]. HVDC cable interties, the best option for long-distance power transmission across the sea since the 1950s [3], are now becoming interesting also for power transmission across the mainland, as witnessed by the huge German Corridors Project in Europe [4]. This renewed interest for HVDC cable systems in both land and submarine links stems from [5–8]:

1) the fear of populations about the electro-magnetic pollution, the soil occupation and the visual impact of overhead lines (OHLs) [9–11]. This holds especially in the European Union (EU), where power demand is still steadily increasing, but public opinion, conservation laws and land owner rights make it very difficult to install new OHLs anywhere;
2) the protection that cables offer from power outages in case of natural disasters such as wildfires, windstorms, cyclones, hurricanes, typhoons, tornadoes, earthquakes, tsunamis, ice storms, floods and landslides [6].
3) the better performances of AC/DC converters—not only of the well-established Line Commutated Current Source Converters (LCCs) but also of the more innovative Voltage Source Converters (VSCs) [1];
4) the reduced losses of HVDC versus High Voltage Alternating Current (HVAC) cables, which imply lower generation for the same amount of electrical energy transmitted to the loads (or conversely same generation for a greater amount of electrical energy transmitted to the loads), thereby saving fossil fuel consumption and CO_2 emissions in case of fossil fuel powered plants [7];
5) the chance of connecting huge Renewable Energy Sources (RES)—which lie frequently in remote locations from large consumption areas—to the grid, thereby fostering decarbonisation and green energy transition in a decisive way [6–8].

Items 1) and 2) are shared with HVAC cables, but items 3)–5) are peculiar to HVDC cables, and specifically items 4) and 5) emphasise that—for crossing large water stretches and urban areas, or when OHLs are not feasible in the mainland due to environmental concerns of the populations, as mostly happens in Europe—HVDC cable transmission is the most efficient and environmentally compatible solution for accessing remote large scale RES (such as offshore wind or desert photovoltaic) integrating bulk renewable power into the grid while providing a power backbone for interconnected AC systems. HVDC allows pan-continental power system integration including asynchronous areas. This makes HVDC cable transmission a key enabler of decarbonisation [5–8].

Focussing on item 4) above, relevant to the lower losses of HVDC versus HVAC cables, the main difference between HVAC and HVDC cables is that the latter miss eddy losses in conductor, screen(s), armouring, neighbouring cables and other metal layers, and have negligible dielectric losses—unless thermal runaway conditions are approached, but this is not the case for a properly designed and operated HVDC cable [12]. Moreover, HVDC cables can afford a higher average working electric field of the cable insulation at the rated voltage than HVAC cables [2, 7]: of course, the higher is the average working electric field of the cable, the thinner is the insulation and the cheaper the cable for a given rated voltage. Insulation compounds for HVDC cables have overall a better endurance to rated voltage than those for HVAC cables, and this enables a better utilisation of HVDC versus HVAC cable insulation. For example, focussing on extruded cables, typically the average design field reaches 15–16 kV/mm at most for HVAC cables [2, 7], 20 kV/mm and more for HVDC cables; design field values > 20 kV/mm for Extra High Voltage Direct Current (EHVDC) extruded cables are witnessed by the recent Cigrè Technical Brochure (TB) 852:2021 [13]. The combination of lower losses and higher working field enables a higher exploitation of the cable, leading to a higher power density per unit-weight (or per unit-length) of cable. One of the ultimate effects is a significant saving of CO_2 emissions, as shown quantitatively in Section 2.

Also, basically three unipolar cables are needed in HVAC cable systems—typically arranged in a horizontally spaced cable layout to promote heat exchange between cables and laying environment, thus maximising ampacity [14, 15]—while 2 (or even 1) unipolar cables are required in HVDC cable systems—in a more compact layout thanks to the lower losses—to transmit the same amount of power [7]. This also implies saving of space occupied by the cable line right-of-way, as also happens for HVDC versus HVAC OHLs [10].

Coming now to item 5) above, the search for massive RES pushes power plants towards remote locations such as far seas with great wind and marine energy wells as well as deserts with large solar energy reservoirs, snowy and remote mountain ranges with abundant hydroelectric resources [8]. The grid connection of such huge and remote RES via HVDC cables is possible as HVDC cable systems do not have practical limits to their length. On the contrary, capacitive reactive power sets a maximum length to HVAC cable systems, ranging from, say, ≈100 to ≈50 km for voltage ranging from 150 to 400 kV (with the additional need of reactive power compensation) [2, 16].

The EU is particularly sensitive to decarbonisation and green transition. Indeed, in its long-term strategy dating back to 2018 [17], the European Commission (EC) singled out offshore RES as a fundamental path towards clean energy transition, and the EC funded 'PROMOTioN' project illustrated the pros of HVDC cable technologies for the reliable grid connection of great offshore RES [18, 19]. In this perspective, HVDC cable technologies also contribute to the global United Nations Sustainable Development Goals (SDGs), especially the following:

- SDG 7 'Affordable and clean energy';
- SDG 13 'Climate action';
- SDG 3 'Good health and wellbeing';

though lower amounts of CO_2 emission and lower cost of electricity (available to all) as HVDC cables transfer more renewable power over long distances to the interconnected AC grid.

Within this context, the present paper first gives some information on the link between the development of new HVDC cable technologies and decarbonisation, including a few simple calculations showing in general terms the quantitative contribution provided by HVDC versus HVAC cable systems to decarbonisation in the EU framework. Then, the main challenges to a long-lasting and reliable design of HVDC cable systems are analysed by summarising the main issues reported in the relevant literature, with focus—for the sake of brevity—on the influence of the various types of cable technologies, of cable laying environment and of duty service. Finally, some hints are also provided at the chances given by multiterminal HVDC cable systems [18].

2 | HVDC CABLES FOR DECARBONISATION IN EUROPE

Since the production and use of energy account for more than 75% of the EU's greenhouse gas emissions, decarbonising the EU's energy system is critical to reach the Paris Agreement, 2030 climate objectives and the EU's long-term strategy of achieving carbon neutrality by 2050. As a one step towards carbon neutrality, the EC aims at increasing the binding target of renewable sources in the EU's energy mix to 40% by 2030 [20]. These ambitious climate targets urge accelerated development of electricity transmission infrastructure in Europe. It is critical to enable the integration of the European energy market and a cost-effective implementation of the 2030 European climate and energy framework. Increased physical interconnections via HVDC cable links across Europe will also create a more competitive European transmission system, and reduce electricity prices for consumers and businesses. In this framework, decarbonisation and climate neutrality are expected by 2050 in accordance with the European Green Deal [20].

Contribution to this wider scheme is also given by developing new technologies for HVDC materials, cables and systems, thereby fostering the reliability and resilience of interconnected HVAC/-DC transmission grids and, in a wider perspective, contributing to the decarbonisation of EU's energy system, provision of cleaner energy at lower costs and increased resilience of the energy system through mitigation of unplanned power outages and blackouts, which will have significant social, economic and political impacts on today's human activities [21].

In the second part of this section, let us try to attain an overall quantitative estimate of the contribution of HVDC versus HVAC cables to decarbonisation in Europe.

First, let us consider the graph of Figure 1 (after [22]), which reports the average Green House Gas (GHG) emission for electricity generation in the EU, *GHGe*, in grams of equivalent CO_2 per kWh over the years from 1990 to 2020. The graph shows that the average *GHGe* in the EU has steadily decreased over these years, also thanks to the massive connection of offshore wind farms (OWFs) lying in the North Sea to the ENTSO-E European grid by means of HVDC extruded cables [5]. Eventually, an average value of 230.7 g of equivalent CO_2 per kWh of electrical energy generation has been reached in 2020, namely $GHGe = 0.231\ \text{tons}(CO_2)/\text{MWh}$.

Then, let us consider that in Ref. [7] (dating back to 2008), the per-unit-weight power carried by an HVDC extruded land cable—say it $P_{\text{HVDC,land}}$—was reported as ranging between 20 and 50 MW/kg, whereas the per-unit-weight power carried by an HVAC extruded land cable—say it $P_{\text{HVAC,land}}$—was reported as ranging between 10 and 20 MVA/kg[1]; these ranges are of course associated with the different possible cable design types—especially for what concerns the conductor type (Cu or Al) and cross-section—as well as with the more or less favourable laying environment [7]. In order to update in general terms these values to state-of-the-art HV extruded land cable technology—so as to account for the improvements in such technology from 2008 to date—the upper boundaries of the above ranges can be taken as reference values, that is, $P_{\text{HVDC,land}} = 50$ MW/kg for HVDC extruded land cables and $P_{\text{HVAC,land}} = 20$ MW/kg for HVAC extruded land cables, when considering also the overall increase of conductor cross-sections in today's HV cables (up to 3000 mm^2 and more) [23].

On these grounds, the CO_2 emissions saved by using an HVDC versus an HVAC extruded land cable—thanks to the lower losses and better utilisation of HVDC versus HVAC cables—can be evaluated resorting to the amount of clean renewable energy carried over one year of operation (consisting of $h_y = 8760$ h) by a unit weight (1 kg) of a state-of-the-art HVDC extruded land cable as follows:

$$W_{\text{HVDC,land}} = P_{\text{HVDC,land}} \times h_y = 50 \times 8760 = 4.38 \times 10^5 [\text{MWh}/(\text{kg})] \quad (1)$$

thereby saving a yearly amount of GHG equal to:

$$GHG_{\text{HVDC,land}} = W_{\text{HVDC,land}} \times GHGe = 4.38 \times 10^5 \times 0.231 = 1.01 \times 10^5 [\text{tons}/(\text{kg})] \quad (2)$$

[1]Here 'per kg' has to be meant as 'per kg of a unit (= 1 m) length of cable over which the power carried by the cable flows'. For example, let us assume that the per-unit-weight power carried by a cable is 20 MW/kg and 1 m of this cable weighs 30 kg: then the power carried by the cable is 20 × 30 = 600 MW.

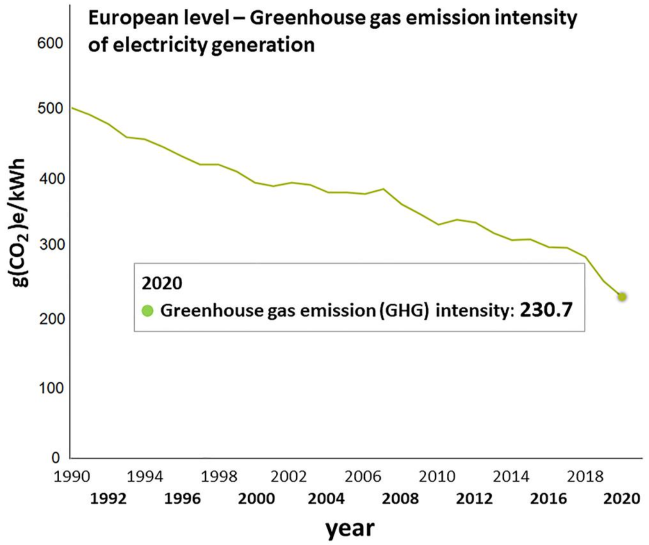

FIGURE 1 Average Green House Gas emission for electricity generation in grams of equivalent CO_2 per kWh (g(CO_2)e/kWh) in the European Union over the years (after Ref. [22])

On the contrary, 1 year of operation with a state-of-the-art HVAC extruded land cable (assuming total reactive power compensation, an upper limit for HVAC cables achievable only with great cost of compensation inductances) [1] would enable carrying an amount of clean renewable energy equal to:

$$W_{\text{HVAC,land}} = P_{\text{HVAC,land}} \times h_y = 20 \times 8760 = 1.75 \times 10^5 [\text{MWh}/(\text{kg})] \quad (3)$$

thereby saving a yearly amount of GHG equal to:

$$GHG_{\text{HVAC,land}} = W_{\text{HVAC,land}} \times GHGe = 1.75 \times 10^5 \times 0.231 = 4.04 \times 10^4 [\text{tons}/(\text{kg})] \quad (4)$$

These calculations reveal that the 'per-unit-weight of cable' amount of GHG saved per year with the HVDC extruded land cable is greater by almost a factor of three compared to the amount of GHG saved per year with the HVAC extruded land cable, in line with the figures from Ref. [7] and the above assumptions. The absolute yearly amount of GHG saved with the HVDC extruded land cable is really impressive, as it is more than one hundred thousand tons of equivalent CO_2.

Of course, similar results can be obtained for submarine cables, although more subtle reasonings are required. Indeed, for state-of-the-art HV extruded submarine cables, the average of the above ranges of values of per-unit-weight power can be considered, due on the one hand to the heavier weight of submarine versus land cables—caused by armouring and reinforcements that are present in the former and missing in the latter [3, 24]—and on the other hand to the positive feedback from the generally lower temperature of the seawater compared to the soil [14, 25]. In this way, a per-unit-weight power $P_{\text{HVDC,subsea}} = (20 + 50)/2 = 35$ MW/kg for HVDC extruded submarine cables and $P_{HVAC,subsea} = (10 + 20)/2 = 15$ MW/kg for HVAC extruded submarine cables can be guessed. Then, Equations (1)–(4) for land cables change are as follows for submarine cables:

$$W_{HVDC,subsea} = P_{HVDC,subsea} \times h_y = 35 \times 8760 = 3.07 \times 10^5 [\mathrm{MWh/(kg)}] \quad (5)$$

$$GHG_{HVDC,subsea} = W_{HVDC,subsea} \times GHGe = 3.07 \times 10^5 \times 0.231 = 7.07 \times 10^4 [\mathrm{tons/(kg)}] \quad (6)$$

$$W_{HVAC,subsea} = P_{HVAC,subsea} \times h_y = 15 \times 8760 = 1.31 \times 10^5 [\mathrm{MWh/(kg)}] \quad (7)$$

$$GHG_{HVAC,subsea} = W_{HVAC,subsea} \times GHGe = 1.31 \times 10^5 \times 0.231 = 3.03 \times 10^4 [\mathrm{tons/(kg)}] \quad (8)$$

These calculations reveal that the 'per-unit-weight of cable' amount of GHG saved per year with the HVDC extruded submarine cable is again greater by almost a factor of three compared to the amount of GHG saved per year with the HVAC extruded submarine cable, in line with the figures from [7] and the above assumptions, although smaller than for land cables due to the lower per-unit-weight power assumed to be carried by submarine versus land cables. The absolute yearly amount of GHG saved with the HVDC submarine cable is still impressive, as it is below but still in the order of one hundred thousand tons of equivalent CO_2.

Of course, these are overall and fairly rough estimates. To refine such estimates, the particular cable designs and laying conditions should be considered for both HVDC and HVAC as well as for both land and submarine extruded cables. Moreover, the choice between HVDC and HVAC cables does not take solely the amount of saved CO_2 into account, but it is a project-dependent decision, based mainly on transmission power, distance, and costs. This decision relies first and foremost on the feasibility of an HVAC connection over the selected transmission distance (see the above-mentioned maximum permissible length of HVAC cables due to capacitive reactive power) and second on an economical comparison between an HVDC versus HVAC cable link [1, 2]. In turn, essential elements for such economical comparison are the fact that HVDC cables are usually cheaper and have very limited losses (see above), whereas the costs and losses of DC converter stations are significantly higher than those of AC transformers and bays; on the other hand, for the HVAC link, the costs of optimised reactive power compensation must be considered [16]. In the end, the line length associated with the transmission distance is the key element for deciding between DC and AC cable systems: above a certain length (which depends on the selected project voltage) DC cables win over AC cables [1, 2], and over such length, the lower losses of DC cable lines further contribute to reduce CO_2 delivery to the atmosphere, fostering the decarbonisation of the electrical system.

3 | MAJOR ISSUES AND CHALLENGES FOR THE LIFE AND RELIABILITY OF HVDC TRANSMISSION CABLES

As shown above, HVDC transmission cables are essential to promote RES and go forward on the way to decarbonisation of the whole electrical system, but of course this requires long-lasting and reliable HVDC cable systems, as long life and high reliability of HVDC cable systems are mandatory requirements for a massive and steady integration of remote renewables into the power network [26]. Moreover, long-lasting and reliable HVDC cable systems are becoming more and more important for the stability and resilience of the whole transmission grid, as HVDC lines and converters—which feature firewall properties against perturbations in the hybrid AC/DC grid—are contributing increasingly to the stable service of the AC network [1]. Furthermore, HVDC transmission systems are coping more and more with the energy marked needs and HVDC merchant lines are becoming a reality [8].

For all these reasons, the operation on duty of HVDC cable systems is much more dynamic than once [1], which involves often unpredictable time-varying load cycles and unconventional transient voltages associated with converter duty service and contingencies in the grid. In addition, the scheme itself of HVDC cable systems is changing from the simple and traditional point-to-point transmission, as the availability of VSC makes multiterminal configurations (Figure 2) easier to implement and manage [1, 18]. As a consequence, multiterminal HVDC transmission arrangements are being devised and promoted by the EU [17, 18].

Focussing on extruded HVDC cables, they are a technology fast moving into the future as their use is being broadened to higher voltage and power ratings [8, 26]. Granting high reliability over their expected lifetime at higher voltages and powers necessitates not only a sound evaluation but also an increase of extruded insulation performances [26]. From this viewpoint, low electrical conductivity at high temperatures and fields, low space charge (SC) retention, good material compatibility, fast and circular manufacturing processes,

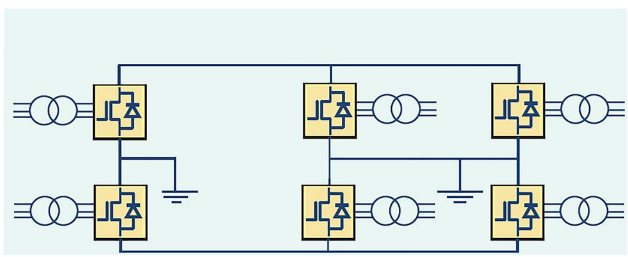

FIGURE 2 Sketch of a voltage source converter high voltage direct current multiterminal arrangement

reliable and robust accessories, ease and eco-compatibility of installation techniques and duty service are the main features for a long-lasting, reliable and environmentally friendly generation of HVDC extruded cable systems, so as to support the green transition, in Europe and worldwide.

On the other hand, seeking remote and massive renewables implies also raising the problems related to the laying environment of HVDC cable systems. Once more, this holds particularly for the newer and less mature extruded technology. Besides satisfactory heat exchange with the soil for land cables and water tightness at high sea depths for submarine cables, the end of life of HVDC extruded cable systems in general is affected by other issues, mostly associated with the fact that they are prone to store SC in the presence of a steady DC voltage [8], as more extensively described in the next sections.

All such trends and problems in this novel and troublesome framework require a thorough R&D effort to investigate the relevant possible influences on the reliability and time-to-failure of HVDC cable systems.

Hereafter, in the paper, the main recent achievements and issues towards long-lasting and reliable HVDC cable systems are analysed by summarising what found in the relevant literature. The focus is—for the sake of brevity—on the influence of the various cable technologies, of the cable laying environment and of the duty service. Some hints are also provided at the chances given by multiterminal HVDC systems.

4 | THE VARIOUS TYPES OF HVDC CABLES

As for the various types of HVDC cables, the market was ruled until the end of the last millennium by oil-paper insulated (or 'lapped') cables—qualified in the past according to Cigrè Electra 189:2000 [27] and now according to the 'fresh' Cigrè TB 853:2021 [28]. The most successful types of lapped cables are Self-Contained Oil-Filled cables and Mass Insulated Non-Draining (MIND) cables [2, 3]. Particularly MIND cables, now qualified for DC voltages up to $\approx \pm 600$ kV [2], are broadly employed since the 1950s for HVDC subsea cable interties [3], as their well-established performance ensures long term reliability. In addition, MIND cables are scarcely affected by Voltage Polarity Reversals (VPRs), therefore they are mostly—but not solely—utilised with Line Commutated Converters (LCCs), which require VPR for inverting the power flow direction [2, 3].

However, after massive theoretical and experimental investigations and developments, at the beginning of the new millennium, HVDC cables with extruded polymeric insulation started being designed, manufactured, installed and commissioned, thanks to the higher maximum conductor temperature, simpler manufacturing, lower weight and lower price, easier installation due to less complex jointing (advantageous especially for land links, where joints are many), and better environmental compatibility (as oil leakage is no more a problem) [2], thereby implying great advantages for both offshore and on-shore applications from the economical, logistic and environmental viewpoints [2, 26]. In some cases, extruded cables are the sole way to prevent unacceptable cable weight—for example, when land HVDC cables are hung on long viaducts, as in the Italy–France intertie [29].

Mainly thanks to the advent of HVDC extruded cables, since 2000 the HVDC cable market has grown a lot all over the world, especially in Europe [5, 8, 26]. Nowadays, the most frequent rated voltage of HVDC extruded cable projects in service in Europe is ± 320 kV (with a capacity of ≈ 1000 MW per bipole) [29, 30], found not only in many subsea links between OWFs in the North Sea and the mainland but also in the France–Spain (INELFE) [30] and Italy–France [29] land interties that connect the EHVAC grids of these countries. The HVDC extruded cable system working at the maximum voltage worldwide is the 'Nemo link' a ± 400 kV-DC submarine interconnection between UK and Belgium in service since 2019 [31]. The highest voltage of HVDC extruded cable projects being installed at present is ± 525 kV-DC and belongs to the huge German corridors [4]. The highest voltage of a HVDC cable system available to the market—qualified according to Cigrè TB 496:2012 [32] in the absence of voltage polarity inversion—is ± 640 kV-DC, with a rated power of a few GW per bipole [23], but the upper voltage limit of HVDC extruded insulated cables is still unknown, but manufacturers are targeting ± 800 kV-DC. The proof is that the voltage limit of applicability of Cigrè testing procedures for HVDC extruded cables has been recently pushed up from the 500 kV of TB 496:2012 [32] to the 800 kV of TB 852:2021 [13].

Looking at the future from such impressive growth in number, voltage and power ratings of HVDC extruded cables, one could expect that because of their above advantages, HVDC extruded cables are overcoming traditional HVDC MIND cables. On the other hand, although more than 2650 km of HVDC extruded cables have been commissioned in the fairly shallow North Sea of Europe to link OWFs to the onshore grid [5], MIND cables are still overwhelming in high depth submarine interties, due to the superlative humidity self-blocking and water-tightness features of HVDC MIND cables and joints. The use of HVDC extruded cables in subsea links is restricted nowadays to a few hundred metres depth, particularly because of water penetration issues in joints [24].

The huge spread of HVDC extruded cables worldwide [23] was made possible by the development of VSCs. Indeed, after some early trials with Poly-Ethylene (PE), Low Density Poly-Ethylene and High Density Poly-Ethylene [2], the most established extruded insulation for HVDC cables consists of cross-linked polyethylene (XLPE) compounds specifically developed for DC applications (the so-called DC-XLPE) [2, 5–8, 24, 26, 33].

Unfortunately DC-XLPE suffers VPRs by much due to the problems caused by SC storage in polymeric insulation under DC voltage. Hence VSCs, which do not require VPR for inverting the power flow direction, are the best converters to use in conjunction with DC-XLPE extruded cables. More in detail, XLPE requires cross-linking of PE, which is obtained by adding a cross-linking agent—typically Di-Cumyl Peroxide (DCP)—to the base compound. Unfortunately, DCP decomposes after cross-linking into the so-called cross-linking by-products—aceto-phenone, alpha-methyl-styrene, cumyl-alcohol, methane etc.—which tend to act as deep SC trapping sites (especially aceto-phenone and alpha-methyl-styrene). The massive SC accumulation under DC voltage and the relevant adverse effects during VPRs are one of the main cons of extruded polymeric insulation [2]. For this reason, the cross-linking degree of DC-XLPE is typically lower and the degassing time (i.e. the time spent in oven after cross-linking to expel volatile cross-linking by-products) is longer than those of AC-XLPE. This also implies slightly lower thermo-mechanical properties of DC-XLPE versus AC-XLPE and leads to a typical maximum permissible conductor temperature in continuous operation (or 'service temperature') of DC-XLPE insulated cables of 70°C, lower than that of AC-XLPE (equal to 90°C) [2, 33].

To assess short- and long-term SC effects on HVDC extruded cable insulation, various SC measurement techniques are now available, among which the Pulse-Electro-Acoustic (PEA) technique and the Thermal Step Method (TSM) seem the most promising for both thin and thick specimens [34]. After plenty of experimental investigations—on flat samples first and on model cables or prototypes later—nowadays the main goal is measuring stored SC in 'as-manufactured' power HVDC cable system components (cables and accessories) laid in the field. The IEEE Dielectrics and Electrical Insulation Society (DEIS) Technical Committee (TC) on 'HVDC Cable Systems (cables, joints and terminations)' has reached this goal for extruded cables by developing IEEE Std. 1732-2017 [35, 36], which recommends a protocol for SC measurements via the PEA and TSM techniques on full-size HVDC extruded cables with rated voltage up to 500 kV before and after prequalification and type-test load cycles after Ref. [13, 32].

Currently, the DEIS TC on 'HVDC Cable Systems' is focussing on the characterisation of HVDC cable system accessories—which are mostly the weak link of HV cable systems—particularly on joints [37, 38]. For this reason, in line with the recommendations after Ref. [13, 32, 39], the TC has identified, developed and standardised a detailed procedure for PD measurement under AC voltage for HVDC extruded cable system joints during routine tests. This eventually led to IEEE Std. 2862-2020, entitled 'IEEE Recommended Practice for Partial Discharge Measurements under AC Voltage with VHF/UHF Sensors during Routine Tests on Factory and Pre-Moulded Joints of HVDC Extruded Cable Systems up to 800 kV' [40, 41].

Coming back to the effect of SC storage on DC-XLPE, further developments of DC-XLPE technology—essentially based on either conductive inorganic nanofillers [2, 33, 42, 43] or polarised inorganic nanofillers [2, 33, 42–44]—have led to commercial DC-XLPE extruded cable systems qualified according to TB 496 [32] for a service temperature of 90°C and in the presence of VPRs, thus also for use with LCC. Notwithstanding this, to the best knowledge of the author only one HVDC extruded cable system is working currently with LCC all over the world, namely the ±250 kV-DC submarine interconnection between Honshu and Hokkaido in Japan [2]. All other HVDC extruded cable links commissioned so far use VSC converters, although the Nemo link cable was qualified also for use with VPRs and has a service temperature of 90°C [31].

As a last, but not least remark about HVDC extruded cable technology, let us also mention a breakthrough that emerged in this field since the mid 2010s with the advent of new polymeric "Poly-Propylene (PP)"-based extruded insulation for HVDC cables. The main reason is that, at the start of 21st century, the search for environmentally friendly, fully recyclable, high performance insulation for HVDC cables pushed R&D towards PP-based thermoplastic compounds, as PP has excellent dielectric and heat resistance properties [26, 45–52]. As a consequence, in the last 2 decades, an extensive R&D activity was carried out on the basic structure of PP, intrinsic modifications, possible nanocomposites. This gave rise to improved electrical, thermal and mechanical properties of PP-based compounds (e.g. Syndiotactic PP [sPP]-based plus PE plus antioxidants) versus XLPE [45–51]. Some studies also highlighted issues of PP-based materials with flexibility, low temperature toughness, overall mechanical properties, which require deeper studies on dielectric properties of such materials [46, 52]. Anyway, nowadays the High Performance Thermoplastic Elastomer (HPTE, or P-Laser™) is the only PP-based insulation commercially available for HVDC cables [26, 53]. HPTE has a service temperature of 90°C, which means greater ampacity than DC-XLPE compounds working at 70°C (see above). An HPTE insulated land cable system has been qualified for use with LCC at a rated voltage U_0 = 525 kV (see Figure 3), thereafter a 600-kV HVDC HPTE cable system has passed the type-test according to Cigrè TB 496 [53].

So far the only HVDC cable transmission system that uses all three extruded insulations for HVDC cables illustrated above—that is, unfilled DC-XLPE, filled DC-XLPE and HPTE—is the already-mentioned German Corridors project, under construction at present [4]. This is a huge set of three ±525 kV, 2 GW, bipolar HVDC links connecting RES in the

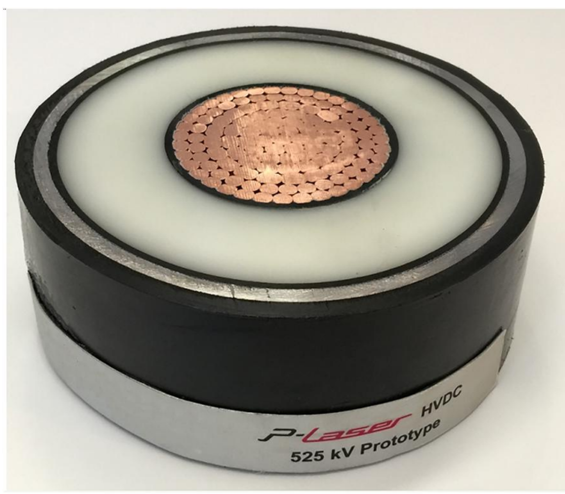

FIGURE 3 525 kV High Performance Thermoplastic Elastomer-insulated high voltage direct current land cable. Courtesy Prysmian

German North Sea to large urban and industrial areas in South Germany. Contracts have been awarded for the German Corridors with both unfilled DC-XLPE, nano-filled DC-XLPE and HPTE insulated cable systems, as summarised in Figure 4 [54–56]. Undoubtedly, the German Corridors represent one of the most relevant steps forward towards decarbonisation in our era.

5 | THE LAYING ENVIRONMENT

Moving on to the effects of the cable laying environment on HVDC cable systems, as hinted above the increased search of great and remote RES is displacing submarine cable lines farther from the shoreline, so as to reach higher sea depths, even resorting to floating offshore platforms in addition to the traditional ones with foundations into the seabed. Therefore HVDC sea cables will encounter more critical conditions both during laying—with stronger winds and waves—and in service—with higher hydrostatic pressure. Such higher static and dynamic mechanical stresses associated with the marine environment will play a significant role on the life and reliability of HVDC subsea cable systems. The increased stresses during laying can be partly tackled with lighter cable designs, aiming at reducing the tensile, bending and coiling—if any—stresses. Lighter cable designs can include, first and foremost, replacing copper with aluminium in the conductor and the use of innovative polymeric armours (for instance made of kevlar) in place of the traditional, but heavier metallic ones [24].

Furthermore, the laying environment is becoming harsher for underground cables too. This holds not only because the search of remote and abundant RES is performed also on the land (e.g. towards far mountain ranges with large hydropower resources) but also as long land HVDC cable links are spreading as well mainly for environmental compatibility reasons (see Section 1). A few instances of this kind in Europe are, as already mentioned above:

1) the ±320 kV-DC VSC, 64-km long, double symmetric monopolar extruded insulation underground INELFE link realised between France and Spain by crossing the Pyrenees mountain range, in service since 2015 [30];
2) the ±320 kV-DC VSC, 190-km long, double symmetric monopolar extruded insulation underground "Italy-France (ITA-FRA)" (or Piemont-Savoie) interconnection in construction between Italy and France by crossing the Alps mountain range [29];
3) the ±525 kV-DC VSC, several hundred km-long, triple symmetric monopolar extruded insulation underground German corridors (see Figure 4), in construction from the large RES in the North to the huge urban and industrial areas in the Centre and South of Germany [4].

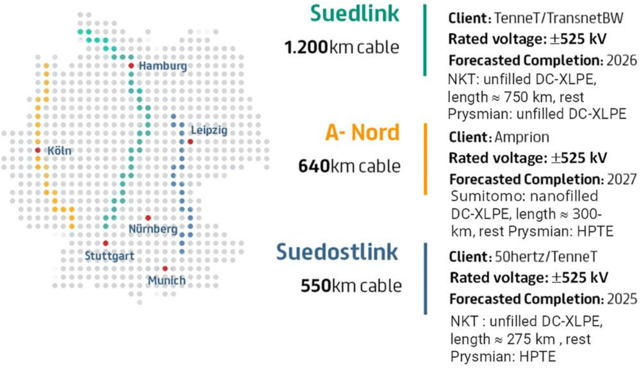

FIGURE 4 Summary of the German Corridors project (after Ref. [54–56])

As it can be noticed, all these interties employ extruded insulation cables for many reasons, among which the better environmental compatibility and the simpler jointing of extruded cables versus oil-paper cables—in fact, the number of joints to be installed in long land links is very high.

These land HVDC cable systems try to follow whenever possible and even share the route of other transport/communication systems and infrastructures to minimise soil occupation. For instance, 70% of the cable route of the ITA–FRA interconnection between Piossasco (Italy) and Grand Ile (France) runs along the highway A32/A43 (Frejus highway), and the cables are laid under the emergency lane or the carriage way [29]; the INELFE link shares the pathway of the High Speed Train between Barcelona (Spain) and Perpignan (France). Of course, the route sharing between HV cables and transport systems requires a sound evaluation of the full compatibility of such synergy 'transport versus electrical power transmission', which in turn involves different branches of engineering [57].

Another issue set by the laying environment to HVDC land cable systems is that in some sections of their route they unavoidably interact with towns and industrial facilities, as well as with sensitive environmental features such as Natural Parks and Protected areas. As a consequence, the type and physical state (moisture, temperature, hardness, porosity) of the soil vary by much in space (i.e. throughout the land cable line pathway) and over time (i.e. day by day, month by month, and season by season). This is clearly shown by the above ITA–FRA and INELFE interties, where the elevation above the sea level also varies by much throughout the line pathway. For this reason, the prequalification test of the ITA–FRA cables according to Ref. [32] included a further subsequent superimposed impulse test with a section of the cable loop cooled at −25°C, to check the ability of the HVDC cable system to withstand the possible risk of permafrost in some sections of the cable route at high altitude and the cold winds when installed under viaducts [29].

All these interactions of the HVDC land cable systems with an ever-changing laying environment result in a continuous change of the laying configuration, that is, from direct burying in the soil, to laying under viaducts, in pipes, in tunnels,etc. As a consequence also the mechanical stress on land cables is more or less strongly non-uniform along the cable pathway, since at some places free expansions and contractions of cables and accessories during load cycles are permitted—for instance if cables are laid in pipes—while elsewhere constraints arise from clamps or fixtures—for instance if cables are laid in tunnels and stuck onto the tunnel walls, or attached to viaducts. For example, the above cited double symmetric monopolar ITA–FRA intertie is fairly-long, totalising ≈760 km of cables; this required a careful planning and optimisation of works to limit the number of joints to be installed as much as possible: this goal was achieved via special drums that are able to carry cable lengths up to 2200 m and special laying systems [29]. Moreover, crossing of several viaducts (1.7 km the longest) and other infrastructures led to minimise cable weight by choosing extruded insulation with aluminium conductor. In addition, special means are adopted to pass from one laying condition to another, and for viaducts crossing, proper stretching absorbers are used along viaduct expansion joints [29].

All such non-uniform and time-varying enhancements of environmental, mechanical, and thermal stresses affect the life and reliability of HVDC cables significantly. For this reason, accurate and sound life and reliability modelling methods have been set up to take into account the changes over space and time of both cable heat exchange with the laying environment and of the mechanical stress during laying operations and duty service of both subsea and land HVDC cable systems [2, 3, 14, 58, 59].

6 | THE DUTY SERVICE OF HVDC CABLE SYSTEMS

As far as the duty service is concerned, HVDC cable systems are moving from the constant operation at rated power with rare inversions of power flow direction—typical of past decades—to a quite dynamic framework. The reasons are manifold.

First, HVDC links foster the stability of interconnected AC networks by smoothening the fluctuations of frequency and voltage and working as a firewall vs. cascaded outages [1].

Second, HVDC links are required to give fast feedback to events as faults of various types, for example, commutation failures of converters, AC-yard or DC-yard faults, short-circuit conditions along AC- or DC-lines etc. This in turn might give rise to unconventional voltage transients added to the rated DC voltage of HVDC cable systems.

Third, related to the former point and hinted at in Sections 1 and 4, HVDC cables are now employed not only with 'traditional' LCCs but also with more innovative VSCs. Apart from being less well established [1, 2], VSC emphasises the above-mentioned unconventional voltage waveforms on HVDC cable systems in the event of DC-side or AC-side faults, the most critical of which are [60–63]:

1) long Temporary Over-Voltages (TOVs), also referred to as very slow front TOV;
2) zero crossing damped TOV [13].

These TOVs require on the one hand a proper assessment of their criticality to HVDC cable systems and on the other hand the development of new testing techniques for establishing the satisfactory behaviour of HVDC cable systems in the presence of such TOVs. The former aspect was thoroughly investigated for the first time from a theoretical viewpoint in Ref. [61, 63, 64]—where an ad hoc procedure based on the previous literature [2, 65, 66] was set up to assess the life fraction lost by HVDC VSC extruded cable systems due to long TOVs and Superimposed Switching Impulses—and from an experimental viewpoint in Ref. [67]. These studies contributed to the investigations by CIGRÉ Joint Working Group B4/B1/C4.73, which has also focussed on new tests for HVDC extruded cable systems subjected to long TOVs [62]. Innovative tests under long and damped TOVs are also recommended for HVDC extruded cable systems in Ref. [13].

Another reason that now makes the duty service of HVDC cable systems more dynamic than in previous years is that HVDC transmission systems are asked to follow as closely as possible the real-time trends of the electricity market. This implies that power flow direction is reversed much more often than in the past; as pointed out above, this reversal is attained by inverting the:

- current direction with VSC, which is not critical to HVDC cable system insulation;
- voltage polarity with LCC, which is particularly harmful to HVDC extruded cable system insulation. Indeed, since the very early R&D on HVDC cable systems, it was clearly shown that VPRs combine adversely with SC storage under DC voltage, which—as pointed out above—is particularly massive in extruded polymeric insulation [2].

For this reason, MIND cables are the preferred choice with LCC, since they withstand VPRs much better than extruded cables; conversely, HVDC extruded cables are never employed with LCC, apart from the Hokkaido-Honshu link cited in Section 4 [2]. However, for MIND cable systems manufacturers prescribe an upper limit to the yearly number of VPRs, and a lower limit of a few hours to the time between consecutive VPRs, in order to rescue also MIND cables from the possible cumulated adverse effects of VPRs [68].

It should also be pointed out that, as for the voltage versus time evolution, two types of VPRs exist, namely:

1) fast VPRs, whereby voltage falls to 0 and then rises to the opposite polarity in some hundred ms, with no relaxation. Fast VPRs serve to respond promptly to contingencies;
2) slow VPRs, whereby voltage falls to 0 in a few hundred ms, followed by some min relaxation time; then it rises to the opposite polarity in a few hundred ms. Slow VPRs serve to follow the electricity market trends.

Thus, modelling the role played by fast and slow VPRs on the life and reliability of HVDC LCC cable systems is of great importance. Aiming at this goal, physical and phenomenological life models were developed: in Ref. [69] for HVDC extruded cable insulation subjected to VPRs under constant load and electric field and in Ref. [68, 70] for full-size HVDC MIND cables subjected to load cycles and VPRs.

In particular, in Ref. [68] focus was on fast VPRs and on the calculation of the transient electric field $E_i(t)$ right after the VPR—where t is the time elapsed since the VPR—at the most severely stressed point within cable insulation; assuming that such field drops exponentially with time t due to the relaxation of the transient SC distribution associated with the VPR, $E_i(t)$ was written as:

$$E_i(t) = E_0 + \Delta E \exp(-t/\tau) \tag{9}$$

where E_0 = rated field before the VPR; $\Delta E = E_{i,\max} - E_0$ = maximum contribution to E_i given by the transient SC distribution associated with the VPR, taking place at once in correspondence of the VPR; τ = SC relaxation time, the time constant governing SC and field relaxation, depending on charge relaxation properties of the insulation.

Then, a heuristic approach was used for deriving τ from test outcomes [68].

Such approach was refined in Ref. [71] by focussing on slow VPRs and making the following hypotheses.

i) The LCC converter is switched off abruptly (in practice in a few hundred ms, see above).

ii) A first transient is accomplished over time t_1 from 0 to $t_{1,\text{end}}$, whereby cable voltage drops with respect to rated DC voltage $+U_0$ (or $-U_0$) and the absolute value of the electric field drops exponentially according to time constant τ due to SC relaxation, that is,

$$E(r, t_1) = E(r, 0)\exp - (-t_1/\tau) \tag{10}$$

Note that it holds:

$$E(r, t_1 = 0) = E(r) \tag{11}$$

$$E(r, t_{1,\text{end}}) = E(r)\exp(-t_{1,\text{end}}/\tau) = E^*(r) \tag{12}$$

that is, the field at the start of the first transient is equal to the constant field in the insulation at constant temperature and without VPR, $E(r)$, while the field at the end of the first transient is equal to a value $E^*(r)$ that depends on $t_{1,\text{end}}$ and τ.

iv) The VPR to $-U_0$ (or to $+U_0$) is completed abruptly, and as a consequence the electric field within cable insulation exhibits an abrupt swing, due to the SC rearrangement.

v) A second transient follows over time t_2 ranging from 0 to $t_{2,\text{end}} = \infty \approx 5\tau$, whereby the absolute value of the electric field $E(r,t_2)$ tends from the value right after the swing to the steady-state value corresponding to $-U_0$ (or to $+U_0$) due to charge relaxation, as follows:

$$E(r, t_2) = E(r) + [E^*(r) + \mathfrak{z}E(r) - E(r)] * \exp(-t_2/\tau) \tag{13}$$

where $\mathfrak{z} \in [0,1]$ depends on charge rearrangement properties of the insulation during the swing, in such a way that:

- for $\mathfrak{z} = 0$, the SC rearrangement during the swing gives no contribution to the inversion;
- for $\mathfrak{z} = 1$, the SC rearrangement during the swing gives the maximum contribution to the inversion.

In Ref. [71], the relaxation time constant τ was estimated from manufacturers' experience with existing MIND HVDC cables in the range from $\tau_{\min} = 12$ min to $\tau_{\max} \approx 24$ min. The life estimates attained in this way agreed well with the experience of TERNA (the Italian "Transmission System Operator (TSO)" about VPR endurance tests on MIND HVDC cables.

As a last remark on duty service, it should be pointed out that VSCs have cons, that is, less service experience records, greater losses and lower reliability than LCCs but on the other hand make a more flexible 'four-quadrant operation' on active and reactive power possible, enable black-start from far renewable power generation units and simplify the realisation of multi-terminal schemes [1, 17, 18]. Indeed, since VSC HVDC transmission reverses power through reversal of the current direction without VPRs, this enables power reversal at intermediate taps, independently of the main power flow direction [1, 18].

VSC Multi-Terminal HVDC (MTDC) grids have been introduced, aiming at a further optimisation of costs and reliability of Voltage Source Converter - High Voltage Direct Current transmission links, for interconnecting complex arrays of power plants and load centres [18, 72–74]. In comparison with the traditional 'two-terminal'—or point-to-point—HVDC transmission, MTDC systems (Figure 2) consist of more than two VSC stations connected through a DC link. Such arrangement allows the connection of all RES (e.g. OWFs) and grids within reach of a transmission network and in turn increases the flexibility and reliability of transmission. Of course, the development of a VSC MTDC grid poses several technical problems being extensively studied in the literature (see e.g. [1, 72–78]), since such grid can be considered as the first truly active transmission network where power flows can be fully controlled in principle and an 'intelligent' control scheme is required to:

1) be able to realise the cleared market bids as actual power injections to the AC grid terminals;
2) remain secure under contingencies;
3) allocate in an optimum way the power mismatches caused by the limited predictability of RES and the needed reserves [74].

Furthermore, it should be pointed out that—as previously mentioned—the service experience of point-to-point VSC–HVDC systems is still limited [62]. Moreover, understanding of MTDC system-level power flow mechanisms and operation under fault and abnormal conditions needs to be improved. In addition, other aspects—although strictly related to these and not often dealt with so far—need also to be addressed, first and foremost the need for an effective governance of this HVDC grid.

7 | CONCLUSION

The increasing power demand, the improved performance of AC/DC converters and the environmental concerns for OHLs have made HVDC cable transmission more and more appealing all over the world, especially in Europe. This has led to a quasi-exponential growth of commissioned HVDC cable lines over the last 2 decades, also because HVDC cable systems appear as the optimum tool for connecting huge amounts of renewables from remote lands and seas to the grid. For these reasons, HVCD cable technologies have been singled out worldwide—and particularly by the EU—as a fundamental tool to increase the penetration of renewables in the electrical energy market, so as to foster the green transition and give an essential contribution to the decarbonisation of our society.

However, HVDC cable system technology is still under development, as higher voltages and powers are targeted for connecting more power to the grid. In addition, harsher environments, as well as more dynamic and challenging duty service, have to be faced on the one hand to increase the penetration of renewables and on the other hand to respond to the quest for greater stability, reliability and availability of the interconnected grid in the framework of the electrical energy market trends.

This paper has tackled most of these issues at a general level, focussing first on a quantitative evaluation of the contribution provided by HVDC versus HVAC cable systems to decarbonisation, and later on the main challenges that HVDC cable systems have to face in this complex framework, in particular on the aspects related to the different cable technologies, the harsher laying environment and the more dynamic duty service.

The main conclusion that can be drawn from such cumbersome picture of different interlinked aspects is that an in-depth dedicated research activity is still needed to improve the performance and reliability of HVDC cable systems, so as to further promote their key role in decarbonisation.

In particular, the new HVDC cable system materials and technologies—for example, thermoplastic insulation for extruded HVDC cables—can provide wide benefits of easier recyclability and reduced carbon footprint. From this viewpoint, the cable design aspects should be considered also from the sustainability point-of-view, with a preliminary evaluation of the influence of the insulation material and its dielectric/thermal/mechanical properties on the overall carbon footprint of the cable system during operation (including e.g. dielectric and conductor losses) so that the new generation of HVDC cables can have improved sustainability figures, compared to the conventional cables, with a reduction of a few tens % of kg CO_2-equivalents over the cable life cycle.

As a matter of fact, HVDC is going to be the transmission technology of our future, as HVDC transmission diminishes the losses and costs and needs less space compared to ac transmission [7]. In a world that is ever more stressed by the growing emissions of greenhouse gases, HVDC transmission is a solution to transport sustainable energy to regions of consumption, decarbonise the power and energy system, and foster the reliability and resilience of inter-connected HVAC/-DC transmission grids. HVDC transmission cables will play a fundamental role in making a cleaner, achievable, sustainable and affordable energy mix available to all. This will not only increase public acceptance of transmission grids but also improve the quality of the life of future generations.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

DATA AVAILABILITY STATEMENT

All the data that support the findings of this study are available in the cited references and websites - apart the calculations reported in detail at Section 2.

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