Compact High Voltage Direct Current (HVDC) Transmission Systems

Kompakte Systeme für die Hochspannungs-Gleichstrom-Übertragung (HGÜ)

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Abstract

Intensive research and development of extruded DC cables took place in early 1990’s. As a result, the first commercial project used ±80 kV and a moderate power level. Innovation in DC insulation materials and manufacturing techniques led to the commercial deployment of extruded high voltage direct current (HVDC) cable systems in different parts of the world. After about 15 years of successful commercial experience, extruded HVDC cables have become a major part of the high voltage cables product portfolio. Over time the number of applications for HVDC cable systems has increased and today the highest voltage in service for extruded DC cable systems is ±320 kV. In 2014, ABB introduced a new voltage level of ±525 kV for extruded cable systems for land and sea applications, which fits with intended voltage levels planned in Europe for expansion of the number of HVDC links.

Nine HVDC systems has been installed or are in construction for integration of offshore wind to the German grid. The majority of these systems use today a voltage level of ±320 kV. Looking ahead, this voltage level appears suitable for offshore connections blocks of ca. 1 GW where collection grids are still of reasonable size. Higher voltages in the offshore power station would also lead to larger air distance clearance of the converter valve and hence (too) large stations.

A major driver for developments of new offshore HVDC connections is the ability to decrease the size of the station. Optimization of the converter station may reduce the size with 50%, which drives down cost of the platform. One component to reduce the size of the station is to shift from air insulated DC switchyard to DC-GIS.

From the successful tests performed so far by ABB and reference installations, it can be expected that DC-GIS components will have equally long lifetime and minimal maintenance requirements as in AC-GIS. The sealed and compact HVDC-GIS installation would give gains both in required land area in switching stations between overhead lines and cables, and in onshore converter stations switchyards.
1 INTRODUCTION

There is a worldwide increasing demand for electrical energy driven by market growth and need to reduce environmental impact of the increase in power demand. Consequently, power generation, transmission, and distribution capability and efficiency must be increased. The two basic alternatives for power transmission are alternating current (AC) and direct current (DC). Nowadays, in many application, especially for transmission of power over long distances and with low power losses, DC is preferred over AC technology. On land, power can be transmitted by overhead lines or underground cables, while for sub-sea transmission power cables must be used. In case of AC cables, the capacitive charging current limits the transmission distance while for DC cable no such limitation exist. Current commercial voltage levels are e.g. 800 kV for overhead line systems [1], whereby 1100 kV are in planning [2] and 500 kV for land and sea cable systems [3]. The higher voltages of 800-1100 kV is applied in countries such as China, India and Brazil whereas the limitation of handling single units of power beyond 1-2 GW makes 500 kV suitable for Europe today.

The European climate and energy 20/20/20, defined by the European Commission [4], requires an adaption of current network structures in Europe. The recent climate negotiation in Paris calls for a speedy implementation of these networks as a main path to introduce renewable energy and harmonizing power markets. One example is the vision of a pan-European energy market exemplified in the generation of the Ten-Year Network Development Plan as drafted by ENTSO-E. Overall, in Europe, a strong demand on sub-sea, long distance, high power transmission is expected, leading to an increase in HVDC system and HVDC cable system development activities (see Figure 1).

Intensive research and development of extruded DC cables took place in early 1990’s. As a result, the first commercial project used ±80 kV and a moderate power level. Innovation in DC insulation materials and manufacturing techniques led to the commercial deployment of extruded high voltage direct current (HVDC) cable systems in different parts of the world. After about 15 years of successful commercial experience, extruded HVDC cables have become a major part of the high voltage cables product portfolio. Over time the number of applications for HVDC cable systems has increased and today the highest voltage in service for extruded DC cable systems is ±320 kV. In 2014, ABB introduced a new voltage level of ±525 kV for extruded cable systems for land and sea applications, which fits with intended voltage levels planned in Europe for expansion of the number of HVDC links.

Gas insulated systems (GIS) enable to optimize the footprint of HVDC converter station switchgear. Small footprints may be needed in special locations to fit the station to the available size. If a mix of underground cables and overhead lines would be used, GIS could also be applied to reduce the footprint of each transition station. Here voltage levels of 500 kV is foreseen.

Since the first installation of Borwin 1 at ±150 kV, nine HVDC systems has been installed or are in construction for integration of offshore wind to the German grid. The majority of these systems use today a voltage level of ±320 kV. Looking ahead, this voltage level appears suitable for offshore connections blocks of ca. 1 GW where collection grids are still of reasonable size. Higher voltages in the offshore power station would also lead to larger air distance clearance of the converter valve and hence (too) large stations.

Figure 1  Design study of 500 kV converter station for the German “Energiewende”
A major driver for developments of new offshore HVDC connections is the ability to decrease the size of the station. Optimization of the converter station may reduce the size with 50%, which drives down cost of the platform. One component to reduce the size of the station is to shift from air insulated DC switchyard to DC-GIS.

2 HVDC SYSTEMS

Today there are two main technologies. HVDC Classic, the first developed technology, is used primarily for bulk electrical transmission over long distances, overland or subsea, and for interconnecting separate power grids where conventional AC methods cannot be used. Today there are more than 100 HVDC installations in all parts of the world. A classic HVDC transmission typically has a power rating of more than 100 megawatts (MW) and many are in the 100 – 10,000 MW range. They use overhead lines, or undersea/underground cables, or a combination of cables and lines. HVDC Light®, developed by ABB and launched in 1997, is an adaptation of HVDC classic used to transmit electricity in power ranges (from 50 – 2,500 MW) transmitted using overhead lines or invisibly, using environmentally friendly underground and subsea cables or gas-insulated lines. It is used for grid interconnections and offshore links to wind farms and oil and gas platforms. In both HVDC Classic and HVDC Light®, it is possible to transmit power in both directions and to support existing AC grids in order to increase robustness, stability and controllability.

Typically, HVDC is a more cost-efficient technology for transmission of large amounts of power over distances exceeding 600 km by overhead lines and about 50 to 100 km in the case of underground or subsea cables. However, many other factors make HVDC technology the ideal complement for evolving AC grids. For example, HVDC Light® systems enable neutral electromagnetic fields, oil-free cables and compact converter stations. Further, they help manage the increasing challenges of renewable energy integration with rapid control of active and reactive power (independently), the provision of voltage support and improvement in power quality. Other advantages – such as black-start capability and the ability to connect to weak AC grids – make HVDC Light® especially attractive for grid interconnections and power provision to isolated systems or crowded metropolitan areas.

![Figure 2 HVDC Light® technology](image)

2.1 HVDC Light®

The HVDC Light® technology, developed by ABB and based on voltage source converters (VSC), has evolved since its introduction in 1997. When the technology’s first generation was introduced, it had the same functionality as HVDC Light® today, but with relatively high losses. The focus of development over the years has been to maintain functionality and reduce losses in order to make it more economical.
The technical development of HVDC Light® technology has been intense the last fifteen years (see Figure 2). The first commercial system was rated 55 MW per block at a voltage level of +/- 80 kV, with an extruded HVDC cable that enabled an underground system that was state of the art. Recently, ABB set an HVDC Light voltage world record with the 500 kV Skagerrak link between Norway and Denmark. ABB has delivered all four of the Skagerrak system’s links: Skagerrak 1 and 2 in the 1970s, Skagerrak 3 in 1993 and now Skagerrak 4. The system spans 240 km and provides 1,700 MW of transmission capacity to enable hydro generation and reservoir storage in Norway to be used to balance wind generation in Denmark. Skagerrak 4 comprises two 700 MW VSC stations [13]. The new link operates in bipolar mode with the Skagerrak 3 link, which uses classic line-commutated converter HVDC technology. This is the first time the two technologies have been connected in such a bipole arrangement.

The converter ratings and possible system configurations are presented in Figure 3 [13]. The voltage of the converter is chosen to enable a base design of the converters that would provide better interoperability and modularity of the systems. The current rating is determined by the size of the semiconductor that is used. The maximum current rating is 1740 A\textsubscript{ac}, corresponding to 1800 A\textsubscript{dc}. The maximum converter rating, 1800 MVA for a single block, is large enough to extend beyond the allowed size of a single power block in many transmission grids, due to the impact of a loss of system.

2.2 Gas-Insulated Systems

The increasing demand for HVDC technology requires the adaptation of gas insulated switchgear (GIS) or lines (GIL), which were originally developed for the AC grid. GIS are particularly relevant for applications where building volume or right-of-way are critical issues, e.g. for mega-city in-feed or densely populated areas in general. The potential of gas-insulated systems for High Power DC (HiPoD) applications was recognized and studied in the 1960s following the first installation in 1983. Nevertheless, the commercial application of HVDC GIS was limited to only few applications. The use of gas-insulated systems was hampered by a tendency for the insulating materials to fail during polarity reversal tests. This was generally attributed to the presence of space charges trapped within the insulation.

The first commercial HVDC-GIS was installed in the year 2000 in Japan. The ± 500 kV HVDC-GIS Anan Converter station of Shikoku Electric Power consists of disconnectors and one bus bar. Since commissioning, the operating voltage is only ± 250 kV. A DC busbar with superimposed DC voltage of ± 150 kV is in operation since 1983/1987 in Gotland (Sweden). In 1986 ABB and BPA have performed together a development of ± 500 kV HVDC-GIS. From 1990 until 1995, long-term tests at BPA’s test center were carried out. The project involved energizing a test pole containing the elements of an SF\textsubscript{6} insulated station for duration of approximately 2 years. The elements of the test pole consisted of GIS spacers, SF\textsubscript{6} air bushings, air insulated arrester, SF\textsubscript{6} insulated arrester, and SF\textsubscript{6} oil bushing. The long term tests were successfully completed in 1996. Today, the increasing demand for HVDC connections for both offshore and onshore applications connected with cost reduction efforts, the goal to be more

![Figure 3 Converter rating as a function of rated DC-voltage and AC-current](image-url)
environmentally friendly is the reason to develop new HVDC gas-insulated systems. The high level of quality of the GIS technology provides security of supply and high availability of electricity. The design of insulating elements for HVAC GIS is optimized for a capacitive field distribution. An intrinsic difference between AC and DC is however that the DC conductivity of insulation materials is strongly temperature dependent, while their permittivity varies only weakly with temperature. As a consequence, the resistive field is enhanced where the DC conductivity is at its minimum, i.e. in cold regions of the insulation. Besides, the accumulation of space and surface charges have to be observed as well as the specific load at superposition of impulse voltages. Using of multi-physics simulation tools the analysis of temperature and electrical field distribution is now possible with high accuracy, taking the following parameters into consideration: temperature and electrical field dependent characteristics of the insulating materials, accumulation of space and surface charges and the superposition of DC and impulse voltages.

New DC insulators for HVDC gas-insulated systems were designed by geometrical optimization and insertion of a current collector. With additional modifications at interface components, like cable termination, and with the development of special current- and voltage transformers, it is possible to use gas-insulated HVDC systems for both onshore and offshore applications in the near future [5]. Just as in AC power systems, the DC-GIS technology spans a number of switchgear components as shown in Figure 4, for example bus-ducts and high voltage DC conductors (A), disconnect- and earthing switches (B), bushings (C) and cable terminations (D), current (E) - and voltage (F) transformer; and surge arresters (G). These components can be applied in various HVDC applications such as DC pole equipment in HVDC converter stations including the DC switchyard, gas-insulated transmission lines, and cable to overhead line transition stations (Figure 4).

Special type tests standards for gas-insulated HVDC systems are not yet available today. In particular, standards for dielectric development tests and possible prequalification tests have to be developed, which take into account the special characteristics of DC applications. Based on development and research results as well as on the service experience, the following dielectric type tests were performed:

- DC withstand voltage test (duration 2 hours)
- Lightning and switching impulse voltage test
- Superimposed lightning impulse voltage tests (bipolar and unipolar superposition)
- Superimposed switching impulse voltage tests (bipolar and unipolar superposition)
- Polarity reversal tests

An intrinsic difference between AC and DC is however that the DC conductivity of insulation materials is strongly temperature dependent, while their permittivity varies only weakly with temperature. As a consequence, the resistive field is enhanced where the DC conductivity is at its minimum, i.e. in cold regions of the insulation. Therefore, all dielectric tests were performed under High Load (HL) conditions.
After a heating-up period, the maximum conductor temperature and maximum temperature drop across the insulation was reached and maintained for the rest of the dielectric HL test. The duration of the heating-up period was determined during continuous current tests and is normally shorter than 8 hours. For heating-up, a DC current or an induced AC current could be used. The effect was already verified in previous continuous current tests and was considered during dielectric testing [6]. Partial Discharge (PD) measurements were performed at maximum continuous operating DC voltage. Some typical defects like hopping particles can be more easily detected by using AC voltages. Therefore, additional PD measurements with AC voltages were performed.

When a DC voltage is applied, the low effective DC conductivity of the alumina-filled epoxy composite solid insulation determines the rate of transition from a capacitive to a resistive field distribution in the system. The transition to a DC field distribution for conventional epoxy insulators takes hours to months. Temperature gradients define primarily, via the temperature dependence of the DC conductivity, where field enhancement and space charge accumulation occurs in the solid, but also shapes the capture volume for ions in the vicinity of the solid-gas interface. Moreover, the surface field can reach its minimum or maximum value during the transition between voltage switch-on and DC steady state. This, associated to the variety of possible operation conditions requires long-term DC insulation system tests [6]. As DC insulation system test, typically more than 10 insulators assembled in realistic arrangements were tested (see Figure 5). A dielectric routine test or preconditioning was considered before starting the insulation system test. The normal sequence of tests was as described in TABLE I.

The time duration $d_{DC}$ of the long duration continuous DC voltage test depends on the transition time from capacitive to resistive field conditions and was calculated before starting the tests. The transition itself depends on the local temperature distribution and on the lowest temperature. Based on a full simulation of the dielectric strength on the insulator surface and the influence of the ambient temperature the test time duration $d_{DC}$ was determined. The time duration $d_{DC}$ of 30 days at an ambient temperature of 40°C was chosen to reach at least 90% of the DC steady field at each location of the insulator surface [7].

The insulation system test was performed under high load conditions. After a heating period the maximum conductor temperature and maximum temperature drop across the insulation was achieved and maintained for the complete test duration. The induced AC current during the test was a little higher compared to the rated current of 4000 A and was adjusted during the test due to changing ambient temperature conditions to limit the conductor and enclosure temperature to the rated temperature limits.
During the entire test partial discharges (UHF PD monitoring), temperature (ambient and test device), test current and test voltage were monitored and the measured data were recorded. The measured temperatures were compared to data obtained from calibration measurements from previous continuous current tests.

<table>
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<tr>
<th>Test</th>
<th>Conditions</th>
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<tr>
<td>Pre-tests</td>
<td>Heating Dielectric Pretests</td>
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<td>Long duration continuous DC voltage test</td>
<td>Maximum continuous operating DC voltage (-) HL</td>
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<tr>
<td>Superimposed lightning impulse voltage tests (bipolar and unipolar superposition)</td>
<td>Rated values HL</td>
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<tr>
<td>Superimposed switching impulse voltage tests (bipolar and unipolar superposition)</td>
<td>Rated values HL</td>
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<tr>
<td>Polarity reversal</td>
<td>HL</td>
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<tr>
<td>Long duration continuous DC voltage test</td>
<td>Maximum continuous operating DC voltage (+) HL</td>
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For gas-insulated systems the DC insulation system test is applicable for LCC and VSC systems. The manufacturer has already successfully finished the DC insulation system test for 320 kV/350 kV gas-insulated systems and the technology is ready for pilot installations. The newly developed voltage transformer was part of the test set-up. Moreover, for the first time the insulation system test was extended by two additional month. CIGRE SC D1 installed a new working group for a short time, which should give recommendations for testing of gas-insulated HVDC systems: JWG D1/B3.57 Dielectric Testing of gas-insulated HVDC Systems. The experience gained by the manufacturers and institutions participating in the development are of help here [9].

3 DC GIS CABLE TERMINATION

In the framework of testing HVDC gas insulating equipment also a cable termination towards the HVDC GIS was developed and tested. The new HVDC GIS cable termination has been developed for the connection of HVDC GIS equipment to an extruded HVDC cable. It consists of a metal housing adopted to the respecting DC GIS solution and is depicted in Figure 6. Inside the cable termination the cable and the metallic connector are mechanically fixed to a cone shaped insulator. Special care has to be taken with the electric stress control close to the cable end, where the ground insulation screen of the cable is terminated. Here, non-linear resistive stress grading technology in combination with a geometrical stress grading is applied to the cable end and located inside the supporting insulating cone. The non-linear stress grading is provided by elastomer elements (adapters, see Figure 6) including a material with highly non-linear electric properties and geometric elements. The geometric grading is supported by an elastomeric stress cone (see Figure 6). The solution for the electrical stress grading of the DC GIS termination is on direct analogy to other HVDC cable accessory equipment of the manufacturer [10], [11].

In operation the DC GIS termination will be subjected to similar stresses as other accessories in an extruded cable system, such as terminations or joints. Specifically, mechanical stresses under load (current) variation are expected. Temperature variations between zero load temperature and full load temperatures, i.e. up to 70°C, may occur in a cable conductor, and results in expansion and contraction behavior of the involved materials. In order to account for such mechanical stresses, as well as for the relevant electrical stresses, the qualification test scheme recommended for extruded cable systems, Cigré
Technical Brochure 496 [12], has been applied. More specifically, the test program suitable for VSC technology at a voltage level of $U_0=320$ kV has been applied.

![CAD drawing of the 320 kV DC GIS termination (left) Example of rubber parts used in the DC GIS termination: field grading adapter (centre) and stress cone (right)](image)

The electrical testing scheme includes a type and a prequalification test. The type test includes load cycling with twelve 24 h cycles at a voltage of $-U_T = -596$ kV, twelve 24 h cycles at $+U_T = +596$ kV and three 48 h cycles at $+U_T = +596$ kV, where $U_T = 1.85 \times U_0$. A cycle involves heating to a maximum conductor temperature $70^\circ$C, followed by cooling before the next cycle starts. After the load cycling impulse voltage testing superimposed to the nominal DC voltage follows. The final step is a 2 h DC voltage test at $U_T$, before examination. The prequalification test (PQ-test, often called long term test) involves a minimum of 360 days DC voltage test including periods of load cycling, high load and zero load according to the scheme in [12]. The PQ-test voltage is $U_{TP1} = 1.45 \times U_0 = 464$ kV. For the HVDC GIS termination the type test has been executed successfully, while the PQ-test is ongoing. Here, two HVDC GIS terminations were tested simultaneously in vertical as well as in horizontal position respectively, see Figure 7 where a test set-up before voltage source application is shown.

![Test set-up for a vertical (left) and horizontal (right) HVDC GIS termination including a cable loop.](image)
4 EXTRUDED HVDC CABLE

Intensive research and development of extruded DC cables took place in the early 1990’s. As a result, the first commercial project used 80 kV and a moderate power level. Innovation in DC insulation materials and manufacturing techniques led to the commercial deployment of extruded high voltage direct current (HVDC) cable systems in different parts of the world. After about 15 years of commercial experience, extruded HVDC cables have become a major player in the portfolio of HV cable products. Over time, the number of applications for HVDC cable systems have increased. In addition, the rated voltage was increased. To date, 525 kV is the highest voltage for extruded DC cable systems (see Figure 8).

For the 525 kV cable, a new grade of non-filled XLPE insulation material with optimized chemical, mechanical and electrical properties was developed. A good HVDC cable insulation material, beside all the normal requirements for HVAC cables, such as good mechanical, chemical and electrical properties, (e.g. high breakdown strength), should meet additional requirements due to the DC voltage. The insulation should have a low DC conductivity to avoid high thermal losses. The conductivity of insulation materials increases with the electric field and temperature, therefore higher conductivity increases the risk of thermal runaway and electrical failure. This risk is highest during the electrical type test of the cable when it is exposed to voltages 1.85 times the nominal operation voltage level. Figure 9 provides a comparison between the conductivity of cables with the previous and the new technology as a function of type test voltage. As for the previous technology the risk of thermal runaway increases when the type test voltage reaches above 600 kV, but with the new technology this risk is negligible even with much higher voltage levels. In this way the new technology provides a platform for producing HVDC cables for higher voltage levels which was physically impossible before [14].
The new XLPE insulation material imposes minimal differences to the current HVDC grade XLPE insulation which is a major advantage. Therefore, relying on ABB’s vast experience in extruded HVDC and HVAC cables and via development of optimal process parameters and quality control techniques, the capability of producing and delivering high quality extruded HVDC cables for land and sea applications for voltage levels up to 525 kV has been established.

The new 525 kV factory joint resembles the actual cable as, in principle. It uses the same materials, e.g. semiconducting and insulating XLPE [13]. This is similar to factory joints for lower voltages. The cable conductors are welded and the semiconducting and insulating layers are restored, utilizing moulding or extrusion. Generally, this process is a challenge as it is time consuming and requires a high degree of cleanliness in the different production steps. This is further pronounced for the 525 kV factory joint, which has additional cleanliness requirements and quality control measures. The factory joints are produced with the same insulation thickness as the cable, leading to similar flexibility and mechanical properties. The pre-fabricated joint consists of a rubber body that is expanded onto the cable and placed over the conductor connector (see Figure 10).

![Figure 10](image)

*Figure 10 Type testing of the 525kV extruded HVDC cable system (left) and a 525 kV rubber body of a pre-fabricated joint (right)*

The 525 kV extruded HVDC cable system is in line with the qualification process according to international standards and recommendations [12]. The electrical testing scheme for cable systems with VSC followed the TB 496. The type test involves load cycling, including twelve 24 h cycles at -972 kV (1.85 x U₀), twelve 24 h cycles at +972 kV and three 48 h cycles at +972 kV. A cycle involves heating to the maximum conductor temperature 70ºC followed by cooling before next cycle starts. Finally, the load cycling impulse voltage testing follows, with a superimposed DC voltage at 525 kV. The impulse levels are here decided by the value the cable system can experience during service, times a factor of 1.15. The last step is a final DC voltage test at 972 kV before examination. A type test circuit is shown in Figure 10. The prequalification test involves a minimum of 360 days voltage test, including periods of load cycling, full load and zero load. The passed test was following the VSC scheme in TB 496 [12]. The final step in the test is a series of superimposed switching impulse tests with opposite polarity at a peak voltage level of 630 kV (1.2 x U₀), in order to check the integrity of the cable after the long term testing.

5 SUMMARY

The trend toward more and larger renewable energy plants is very clear and very strong. HVDC technologies will help support interconnected, flexible and reliable grids. Many innovative and sophisticated products are already available to help overcome the challenges involved with renewable energy integration and enhance the power system flexibility and efficiency required to satisfy the ever-growing need for energy around the world. The development of VSC HVDC Converters and extruded HVDC Cables has enabled new applications for transmissions system owners. Technology solutions for HVDC systems up to 1.8 GW that incorporate higher control and dynamic features enable high performance system as part of the planning toolbox for future transmission solutions.

A HVDC GIS installation can be built with a much higher degree of compactness and significantly lower sensitivity to ambient factors than with air-insulated switchgear (AIS). The most obvious cost-saving
potential can be found on offshore converter platforms. At present nine offshore HVDC links have been delivered or are under construction. As example the DolWin2 project, offshore wind farms will be connected to an HVDC converter station installed on an offshore platform in the North Sea. The transmission system will have a total capacity of 916 MW at ± 320 kV, which will make it the world’s largest offshore wind HVDC grid connection.

![Figure 11 A 3-D model (left) and photo (right) of the self-installing steel gravity base structure (GBS) platform for Dolwin2](image)

Such converter stations are at present challenging to handle during construction and installations phases. High dependence on weather conditions and supporting structures could be mitigated if the platforms size could be reduced. Such compactness would not only bring down the cost of the platform but also render additional cost savings due to flexibility during construction and installation. All AC connections to the platforms are already GIS, so the opportunity to use compact HVDC-GIS would be an immediate advantage in design of the platforms. Hence, long air-clearances at a DC voltage of ±320 kV for the AIS switchgear leads not only to much larger and heavier offshore structures, but also limits the design options. By using HVDC-GIS, the volumetric space of the switchgear installation itself can be drastically reduced e.g. by 70%-90%, which may results in a size reduction of circa 10% of the total platform and a compact building block for planning of the offshore station layout. If future offshore grids would be considered with multi-terminal or switching stations off-shore, the gain would be considerably larger.

Specific type tests standards for gas-insulated systems specific for HVDC are not yet available today. Based on insulation co-ordination studies, test values were defined, which take all technical aspects into account. Based on the development and research results combined with the service experience new type test philosophy including insulation system tests were developed. ABB has already successfully finished the verification tests 320 kV/330 kV gas-insulated insulators and the technology is ready for its pilot installation. Once dimensioning guidelines have been established, development of higher voltage ratings will follow.

From the successful tests performed so far by ABB and reference installations, it can be expected that DC-GIS components will have equally long lifetime and minimal maintenance requirements as in AC-GIS. The sealed and compact HVDC-GIS installation would give gains both in required land area in switching stations between overhead lines and cables, and in onshore converter stations switchyards.
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[12] CIGRE Technical Brochure 496: Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500 k, April 2012
