The new 525 kV extruded HVDC cable system
World’s most powerful extruded cable system

Anders Gustafsson, Markus Saltzer, Andreas Farkas,
Hossein Ghorbani, Tobias Quist, Marc Jeroense

High Voltage Cables
Grid Systems
Power Systems

Summary

This new 525 kV DC cable system with a power rating range of up to 2.6 GW was developed for both subsea and underground applications. The extruded HVDC cable system technology is appropriate when power needs to be efficiently delivered through populated or environmentally sensitive areas, or in coastal and open-sea applications. HVDC cable links are essential components of sustainable energy systems to connect energy markets and transmit vast amounts of electricity over very long distances, across or between continents.

The successfully tested extruded 525 kV HVDC cable system is the result of ABB’s continuous investment in the development of innovative technology, and creates an exciting future for power transmission. This innovative system utilizes a new cross-linked polyethylene (XLPE) DC insulation material, an oil- and porcelain-free termination based on ABB’s technology for bushings as well as a land joint and a flexible sea joint.

This technical paper describes the product development including challenges and solutions, for the cable as well as the accessories, the extensive testing procedures and what the cable system is able to do.

Keywords: HVDC cable, extruded, 525 kV, non-linear field control

1. Introduction

Intensive research and development for 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 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 (Table 1).
Over time the number of applications for HVDC cable systems has increased. The highest voltage on the market today for extruded DC cable systems is 320 kV. Extruded HVDC cable systems enable, for example, solutions for the connection of remote energy resources to the loads, while circumventing public and land owner opposition to the construction of new overhead lines.

This technical paper describes a new step in the development of extruded HVDC cable systems. ABB has qualified an extruded DC cable system at the 525 kV level including joints for both land and sea as well as terminations. This development is a major step in enabling the DC grid vision and for integration of energy markets and greater utilization of renewables.

Table 1. Extruded DC (HVDC Light) cable systems from ABB, [km] are cables installed.

<table>
<thead>
<tr>
<th>Project</th>
<th>Country</th>
<th>Year</th>
<th>Voltage [kV]</th>
<th>Submarine [km]</th>
<th>Land [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gotland</td>
<td>Sweden</td>
<td>1998</td>
<td>80</td>
<td>0</td>
<td>140</td>
</tr>
<tr>
<td>Directlink</td>
<td>Australia</td>
<td>1999</td>
<td>84</td>
<td>0</td>
<td>390</td>
</tr>
<tr>
<td>Murraylink</td>
<td>Australia</td>
<td>2002</td>
<td>150</td>
<td>0</td>
<td>360</td>
</tr>
<tr>
<td>Cross Sound</td>
<td>USA</td>
<td>2002</td>
<td>150</td>
<td>83</td>
<td>0</td>
</tr>
<tr>
<td>Troll A</td>
<td>Norway</td>
<td>2004</td>
<td>60</td>
<td>284</td>
<td>0</td>
</tr>
<tr>
<td>Estlink</td>
<td>Estonia-Finland</td>
<td>2006</td>
<td>150</td>
<td>266</td>
<td>62</td>
</tr>
<tr>
<td>BorWin 1</td>
<td>Germany</td>
<td>2009</td>
<td>150</td>
<td>372</td>
<td>155</td>
</tr>
<tr>
<td>EWIP</td>
<td>Ireland-UK</td>
<td>2012</td>
<td>200</td>
<td>320</td>
<td>152</td>
</tr>
<tr>
<td>DolWin 1</td>
<td>Germany</td>
<td>2013</td>
<td>320</td>
<td>170</td>
<td>187</td>
</tr>
<tr>
<td>SouthWest link</td>
<td>Sweden</td>
<td>2014</td>
<td>300</td>
<td>0</td>
<td>797</td>
</tr>
<tr>
<td>NordBalt</td>
<td>Sweden-Lithuania</td>
<td>2015</td>
<td>300</td>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td>Åland-Finland</td>
<td>Finland</td>
<td>2015</td>
<td>80</td>
<td>318</td>
<td>0</td>
</tr>
<tr>
<td>DolWin 2</td>
<td>Germany</td>
<td>2015</td>
<td>320</td>
<td>99</td>
<td>183</td>
</tr>
</tbody>
</table>

2. The product development

The development and commercial introduction of extruded HVDC cable systems started in the 1990’s at the 80 kV level. After the introduction of 150 and 200 kV level cable systems the level of qualification and commercial deliveries is presently 320 kV (Table 1). Quite quickly after this qualification ABB decided to go further and to take the next step in the development.

Several required properties and improvements were identified and initiated. This was not just for the cable itself, the accessories (i.e. joints for both land and sea as well as terminations) also needed to attention.

Cable

A close collaboration between the R&D centers of ABB and Borealis was established to develop a robust insulation material system for higher voltage HVDC cables. A wide range of insulation materials including thermoplastics, cross-linked insulation systems, polymer blends, filled and non-filled insulations were studied. Finally a new grade of non-filled XLPE insulation material with optimized chemical, mechanical and electrical properties was developed. Cables from model to full scale cables were produced and tested.

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 1 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.

![Comparison on conductivity vs voltage for the new and previous HVDC cable insulation system.](image)

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.

In the production of power cables a very strict quality assurance system is required since a small flaw can affect the function on hundreds of kilometers of cable, therefore the production units should have and maintain very consistent high quality. In classical HVAC power cables, the insulation should be clean of voids, cracks, deformations, pollution particles and scorch, etc. In HVDC cables, beside the quality requirements of HVAC power cables, extra quality requirements shall be considered. For example, the presence of many chemical compounds which are not harmful to the AC cable function, can affect the DC conduction in HVDC cables and therefore the DC insulation should be protected against such species. Being aware of the importance of quality, an extensive review and update of the quality assurance system of ABB’s HVDC cable system has been performed. The quality assurance system covers the whole chain from the insulation material production and quality control (QC) to cable
production, routine tests and the installation of the cable system including the cable accessories.

Joints

Joint devices are used for connecting two cable ends in an extruded cable system. Here, two types of joints are common: factory joints and prefabricated joints. Often they may also be referred to as sea (factory) and land (prefabricated) joints. This relates to the transport situation in land, where short cable sections are transported to the laying site on drums, and many joints need to be installed on site. Contrary, the boats transporting sea cables to the site may load hundred kilometers and more, and required jointing can be done prior to loading and transport under factory conditions.

The new 525 kV factory joint resembles the actual cable as, in principle, it uses the same materials, e.g. semiconducting and insulating XLPE. This is similar to factory joints on lower voltages. The cable conductors are welded and the semiconducting and insulating layers are restored utilizing molding 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. Ideally, factory joints are produced with the same insulation thickness as the cable, leading to similar flexibility and mechanical properties. A factory joint in a fully armored cable can hardly, if at all, be differentiated from a normal cable section. Despite the increased requirements on cleanliness and quality measure, the new 525 kV factory joint has not increased in required mounting time compared to those with lower voltage levels.

In order to overcome the production/mounting time limitation from factory joints, a joint body can also be pre-molded. This prefabricated joint is then installed on site by simply sliding it onto the cable. Contrary to the factory joint, where the insulation material is applied directly onto the conductor, the prefabricated joint is mounted onto the insulating section of the cable. Therefore it is considerably larger in diameter than the cable itself. While a factory joint can have a mounting time of up to two weeks, a 525 kV prefabricated joint can be mounted within one or two days. Moreover the production steps are such that two joints can be mounted at the same time. Containers specifically built for the jointing on site, allow to maintain a high level of cleanliness and control at site. Figure 2 shows a prefabricated joint after installation on a land cable system including screen separation.

![Figure 2: New HVDC prefabricated joint after installation in a land cable system.](image)

A prefabricated joint, similar to a factory joint, needs to resemble all essential parts of the cable, i.e. a HV conducting side, a ground conducting side and insulation in between. However, due to the mechanical and production requirements the materials of the prefabricated joint differ from the cable material. Typically, the DC properties of the different
(joint and cable) insulation materials can cause unstable field distribution in the jointing area of a prefabricated joint when increased DC voltage is applied and temperatures vary. In order to prevent these problems ABB has selected the patented non-linear resistive stress grading technology in combination with a geometrical stress grading for the new 525 kV prefabricated HVDC joint. This makes the joint very robust under DC voltage load cycling and dynamics such as impulse. This is sketched in Figure 3 showing essentially the different material layers of an ABB joint for an extruded HVDC cable. An inner deflector made of a semi-conducting rubber attaching to the connector on HV potential, a layer of insulating rubber represents the actual joint insulation, an outermost layer of the joint body is made up of a semi-conducting rubber screen, and in building the interface from the prefabricated joint to the cable, a continuous layer of non-linear resistive stress grading material, which also covers the inner deflector or the metallic connector.

![Figure 3. Typical ABB HVDC prefabricated joint design with a FGM layer. The joint can simply slide over the cable.](image)

Among others, the essential property of the non-linear resistive material layer is that its electrical conductivity is strongly electrical stress dependent. It will control its internal electrical stress by adjusting its conductivity if the electrical field increases.

In the same way it dominates the stress distribution in the adjacent insulating layers of the cable and the joint, making this joint a very robust system under load changes. Also fast transients such as impulse wave shapes can be effectively graded by controlling the onset values as well as the time scale on which the material should act by the proper choice of the conductivity’s electrical field and temperature dependence. With today’s non-linear stress grading technology based on SiC or ZnO microvaristor filled polymers, the stress grading characteristics can be fine-tuned by the appropriate choice of process parameters. Of course, know-how in the area of non-linear stress grading materials is a prerequisite for the proper design and development of such materials for HVDC extruded cable accessories. Specifically, for the new 525 kV prefabricated HVDC joint, a special combination of non-linear resistive and geometric stress grading is utilized.

**Terminations**

The cable terminations of the 525 kV extruded HVDC cable system connect to overhead bus bars and can be installed indoors and outdoors.

The termination development is based on existing ABB HVDC bushing technology. Know-how from the 800 kV HVDC bushing development has been utilized. The polymeric composite insulator offers maximum safety without the risk of shrapnel from explosions. The corona ring also has a special design that has a proven high robustness for DC under
strongly varying environmental conditions. The inside of the new 525 kV HVDC termination is filled with dielectric gas (SF\textsubscript{6}) that is inflammable and does not contaminate the soil. Special care has to be taken with the electric stress control close to the cable end inside the termination. Here, a similar situation to the joint for connecting two cables applies for connecting a cable to a high voltage end. Similar to the prefabricated joint ABB has selected to apply non-linear resistive stress grading technology in combination with a geometrical stress grading to meet the high requirements of stability during transients, no matter whether they are slow such as load cycles or fast such as impulse shapes. This is provided by elastomer elements (adapters and stress cone) including a material with highly non-linear electric properties and geometric elements. The new 525 kV HVDC cable termination is shown in Figures 5 and 6.

3. Testing

The 525 kV extruded HVDC cable system is in line with the qualification process according to international standards and recommendations. The latest document governing the qualification of extruded HVDC cables is the CIGRE Technical Brochure (TB) No. 496 which was issued in April 2012. Mechanical testing and other tests not specific to HVDC cables are based on IEC standards whereas the electrical testing is in TB 496.

Figure 5. Extruded HVDC cable termination.

Figure 6. Type testing of the 525 kV extruded HVDC cable system.
After the research on plate samples the development testing started on smaller experimental and prototype cables. The final selection of the insulation system and the accessories continued to be tested on full-scale cables. The last step in the qualification is to fulfil the type test and the prequalification test (also called long term test).

ABB has excellent in-house test facilities and equipment for the extensive qualification and type test process for cable systems. Figure 6 shows the type test set-up for the cable system including the two terminations and the land and sea joints.

4. **Possibilities with a new more powerful cable system**

The 525 kV extruded DC cable system can transmit at least 50% more power over extreme distances than previous solutions (i.e. the 320 kV extruded DC system). The technology enables the lowest cable weight per installed megawatt (MW) of transmission capacity and the higher voltages provide reliable transmission and low energy losses.

Figure 7 shows the transmitted power as a function of conductor area for both copper and aluminium as the conductor material. It is possible to transmit up to 2.6 GW through one pair of cables with the 3000 mm² copper conductor. Compared with the 320 kV level the transferred power given as MW/kgm (power per kilogram of one meter cable) is about doubled for a land cable circuit and 1.5x for a submarine circuit for a transmitted power of 1.5 GW (Figure 8).

![Graph showing transmitted power as a function of conductor area and metal for a cable pair. The Copper (3000 mm²) and Aluminium (2000 mm²) 525 kV cables are shown to the right.](image)

When comparing with the “classic” HVDC cables and their insulation system of paper impregnated with a highly viscous oil (also called mass impregnated, MI) the extruded DC cable system has a big advantage in terms of MW per kg and meter cable. The effect is greater for the land cable since MI cables need lead as a next layer after the insulation and the lower operating temperature (Figure 9). Also jointing time of an underground cable is much shorter for an extruded cable system compared to the MI cable.
5. Outlook and Conclusion

The qualification of the 525 kV extruded DC cable system is a significant step within the high voltage cable system field towards fulfilling pending customer requirements. A new cable insulation system is qualified together with an underground (land, prefabricated) joint, a flexible submarine joint and terminations in which oil and porcelain is replaced with gas and a composite insulator.

This achievement is the result of vast research and experience from the preceding extruded HVDC cable systems with input from new angles. It is also the outcome of a fruitful collaboration with Borealis regarding the cable insulation system and a wide and strong collaboration between several ABB units including the corporate R&D centers. Furthermore, the success is also due to extensive interaction between different disciplines such as materials technology, analytical chemistry, physics, electrical engineering and project management.

6. Bibliography

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