Qualification of an extruded HVDC cable system at 525 kV

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ABSTRACT

A new 525 kV DC cable system with a power rating range exceeding 2 GW has been developed for both subsea and underground applications. The extruded HVDC cable system technology is appropriate when power needs to be delivered efficiently through populated or environmentally sensitive areas, or in coastal and open-sea applications.

The successfully tested extruded 525 kV HVDC cable system is the result of long-term focused R&D work and collaboration with a material manufacturer. This system utilizes a new cross-linked polyethylene (XLPE) DC insulation material, an oil- and porcelain-free termination based on HVDC wall bushing technology as well as a land joint and a flexible sea joint.

KEYWORDS

HVDC, extruded cables, 525 kV, non-linear field grading materials, composite insulators

INTRODUCTION

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 player in the portfolio of HV cable products.

Over time the number of applications for HVDC cable systems has increased and the highest voltage in service today for extruded DC cable systems is ±320 kV.

The 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 [1][2].

CABLE DEVELOPMENT

A good HVDC cable insulation material, besides all the normal requirements for HVAC cables, such as good mechanical, chemical and electrical properties, (e.g. high breakdown strength), has to meet additional requirements due to the DC voltage. The insulation shall 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 testing 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 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 impossible before.

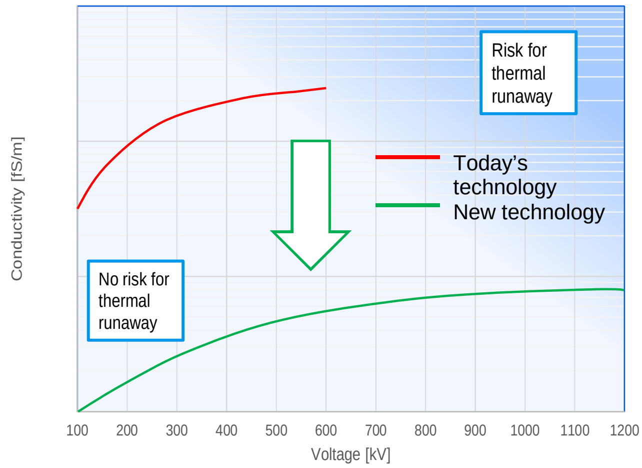

Figure 1: Comparison on conductivity vs voltage for the new and previous HVDC cable insulation system.

Several material compositions were evaluated during the initial stages of the development. Based on several parameters for producing and qualifying full-scale cables the new compound is based on XLPE. References [3] to [6] describe the XLPE compound development and it characteristics in more detail.

The new XLPE insulation system is closely related to the one presently used which is a major advantage. The development of optimal process parameters and quality control techniques has enabled the capability of producing and delivering extruded HVDC cables at higher voltage levels.

Figure 2: 525 kV cables with Aluminium or Copper conductor.

In the production of the HVDC power cables (Figure 2) a very strict quality assurance system is required since a small flaw can affect the function on hundreds of kilometres of cable, therefore the production units shall 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 HVAC quality requirements, 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 is to be protected against such species. The quality assurance system covers the whole chain from the insulation material production and quality control to cable production, routine tests and the installation of the cable system including the cable accessories.

CABLE ACCESSORIES DEVELOPMENT

<u>Joints</u>

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.

Factory joints

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 moulding or extrusion. Generally this process 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. A factory joint in a fully armoured 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 does not require a longer mounting time compared to those at lower voltage levels.

Pre-fabricated joints

In order to overcome the production/mounting time limitation from factory joints, pre-fabricated or pre-moulded joints are used. The pre-fabricated joint is installed on site by expanding it onto the cable. While a factory joint can have a production time of several days, a 525 kV pre-fabricated joint can be mounted within one or two days. Containers specifically built for the jointing on site, allow to maintain a high level of cleanliness and control at site (Figure 3).

Figure 3: Specifically built container for underground cable jointing.

Figure 4 shows a pre-fabricated joint body before installation and Figure 5 shows a final pre-fabricated joint on a land cable system including screen separation.

Figure 4: The new HVDC prefabricated joint body before installation.

Figure 5: New HVDC prefabricated joint after installation in a land cable system.

A pre-fabricated 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, the pre-fabricated joint differ from the cable material. Typically, the DC properties of the different (joint and cable) insulation materials can cause instable 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 a patented non-linear resistive stress grading technology in combination with a geometrical stress grading has been selected for the 525 kV pre-fabricated HVDC joint. This makes the joint very robust under DC voltage load cycling and voltage transients such as impulse voltages. This is sketched in Figure 6 showing essentially the different material layers of the joint for the extruded HVDC cable. An inner deflector made of a semi-conducting rubber attaching to the conductor connection, a layer of insulating rubber, an outermost layer 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.

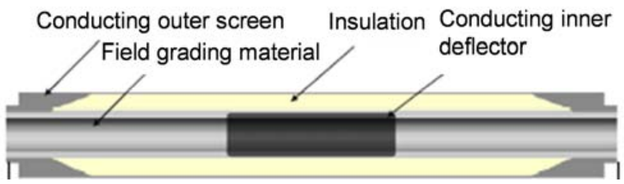

Figure 6: Typical HVDC prefabricated joint design with a field grading material layer. The joint can simply slide over the cable.

The essential property of the non-linear resistive material layer is that its electrical conductivity is strongly dependent on the electrical stress. It will control its internal electrical stress by adjusting its conductivity if the electrical field increases [8].

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 voltages can be effectively handled by controlling the strength and onset of the nonlinear electric field dependent conductivity.

The new 525 kV prefabricated HVDC joint has a combination of non-linear resistive and geometric stress grading.

Terminations

The development of the termination is based on know-how from the 800 kV HVDC wall bushing development. The polymeric composite insulator offers maximum safety without the risk of shrapnel from explosions. The corona ring also has a 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_6) that is inflammable. Special care has to be taken with the electric stress control close to the cable end inside the termination. Similar to the prefabricated joint, a non-linear resistive stress grading technology in combination with a geometrical stress grading is used. This is provided by elastomer elements (adapters and stress cone, see Figure 7) including a material with highly non-linear electric properties and geometric elements.

The new 525 kV HVDC cable termination is shown in Figure 8.

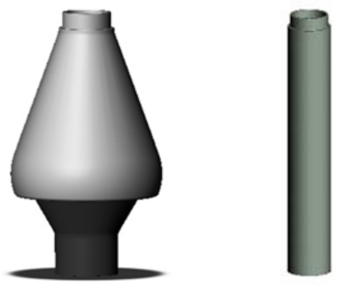

Figure 7: Rubber parts in the 525 kV DC termination: stress cone and field grading adapter.

Figure 8: Termination for Extruded HVDC cable with composite insulator.

QUALIFICATION

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, issued in April 2012 [9]. Mechanical testing and other tests not specific to extruded HVDC cables are based on IEC standards whereas the electrical type testing is outlined in TB 496.

After research experiments on plate samples the development testing started on experimental and prototype cables of smaller size than the final full-scale 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.

Type test

The type test includes, as for the type test in HVAC cable systems, a mechanical preconditioning of the cable such as a bending test before starting the electrical testing. This is to resemble the handling of the cable during e.g. installation on site.

The electrical testing scheme for cable systems with VSC (Voltage Source Converters) was followed according to TB 496. The load cycling includes twelve 24h cycles at -972 kV (1.85 x U_0), twelve 24h cycles at +972 kV and three 48h cycles at +972 kV. A cycle involves heating to the maximum conductor temperature 70ºC followed by cooling before the next cycle starts. After 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.

Two type tests have been passed successfully on two separate 525 kV DC cable system set-ups as described above (Figure 9).

Figure 9: Type testing of the 525 kV extruded HVDC cable system.

Prequalification test

The prequalification test (PQ-test, often called long term test) involves a minimum of 360 days voltage test including periods of load cycling, full load and zero load according to a scheme in TB 496. The overall cable system set-up is basically the same as for the type test except that there is a requirement that the cable length is at least 100 m.

The passed test was following the VSC scheme for the long duration voltage test. The final step in the PQ-test is a series of superimposed switching impulse tests with opposite polarity at a peak voltage level of 630 kV (1.2 x U_0) in order to check the integrity of the cable after the long term testing.

Measurements during the prequalification test

During the prequalification (PQ) test, the cable system is tested at different thermal conditions while constant DC voltage is applied. The test includes 8 blocks (each 40 days) of electrical testing with DC voltage of 1.45 times the U_0 (751.3 kV for U_0 = 525 kV); the test starts with two blocks of load cycling with both voltage polarities, followed by two blocks of constant heating (High Load or HL) with both polarities, one block of no load test with negative polarity and finally two blocks of load cycling with both polarities.

During the whole test, the temperature of the outer jacket of the cable is measured at multiple points in the circuit. For example, the temperature of the outer jacket measured during four load cycles is presented in Figure 10.

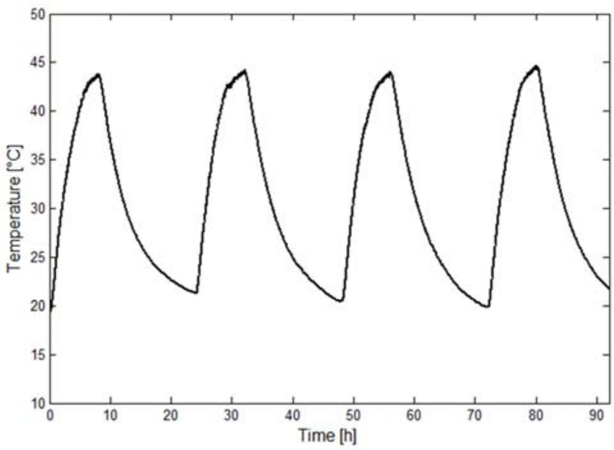

Figure 10: Measured sheath temperature of the cable during 4 load cycles of the PQ test.

Since the PQ test is rather long, it is of interest to check its effect on the physical properties of the cable insulation especially the electrical conduction properties. Therefore, during the whole duration of the PQ test, the conduction current of the cable was measured and stored every minute; Figure 11 shows the measured leakage current in a cable section during the first four thermal cycles of the PQ test.

Via tracking the measured leakage current of the cable through the PQ test, it is possible to verify that the electrical and thermal stresses do not worsen the electrical properties of the cable system. Figure 12 shows the measured leakage current with 70 °C on the conductor for every day of the PQ test with heating. Note that the Zero Load block is not included in this plot because in this block no heating was applied.

During each test block, with constant voltage, the measured leakage current decays slowly towards a stable value. This is repeated for each block after each change of polarity. The measured values after the last block of the test are similar to the measurements after the first block which means that no detectable electrical aging has occurred in the system.

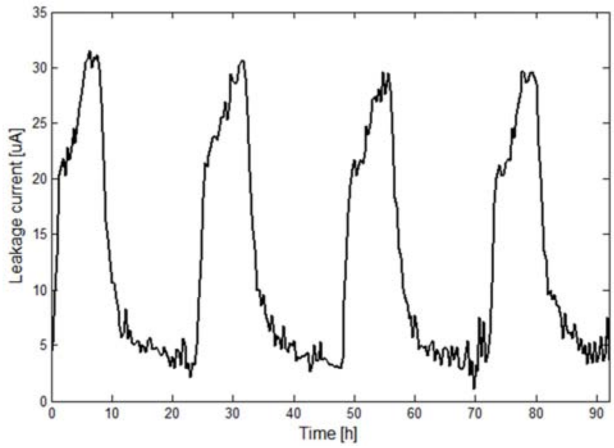

Figure 11: Measured leakage current of the cable during the first four load cycles of the PQ test.

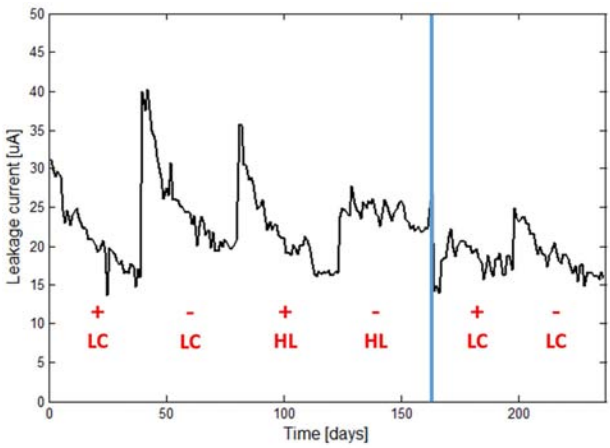

Figure 12: Leakage current of the cable with 70 °C on the conductor, measured for every day of the PQ test with heating on. The polarity of the voltage and the type of heating (LC: Load Cycling or HL: High Load) is shown for each block. The vertical line shows time of the Zero Load (ZL) block [9].

In order to obtain information about the cable, thin (200 µm) films were peeled from the cable insulation after the PQ test. The electrical DC conductivity was measured with 30 kV/mm at 70 °C and different radial positions through the insulation, see Figure 13.

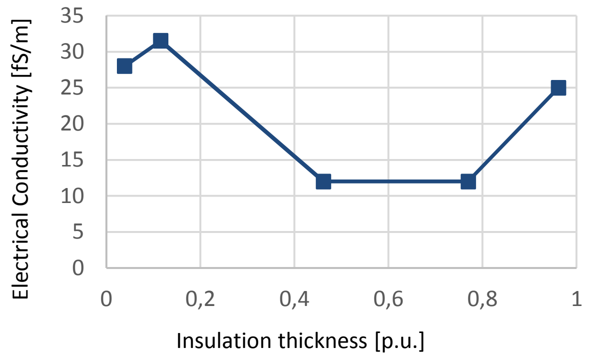

Figure 13: Electrical DC conductivity of thin films peeled from cable insulation prior after the PQ test; measured at 70 °C with 30 kV/mm.

The measured conductivity levels are in good agreement with the expected values from press moulded samples [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 14 shows the transmitted power as a function of conductor area for both copper and aluminium conductor. It is possible to transmit up to 2.6 GW through one pair of cables with the 3000 mm^2 copper conductor. Compared with the 320 kV level the transferred power given as MW/kg/m (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 15).

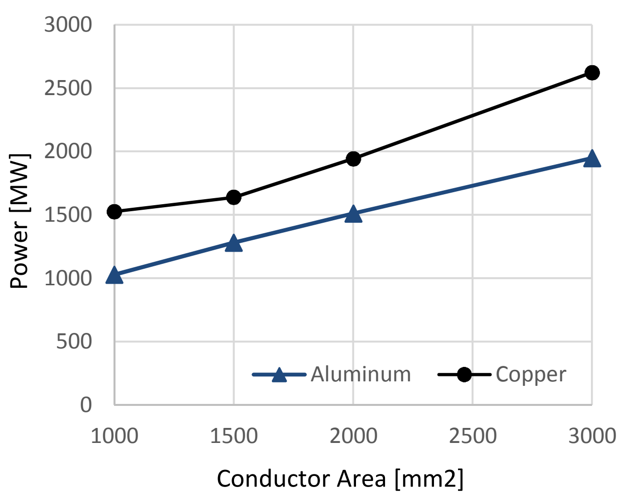

Figure 14: Transmitted power as a function of conductor area and metal for a cable pair.

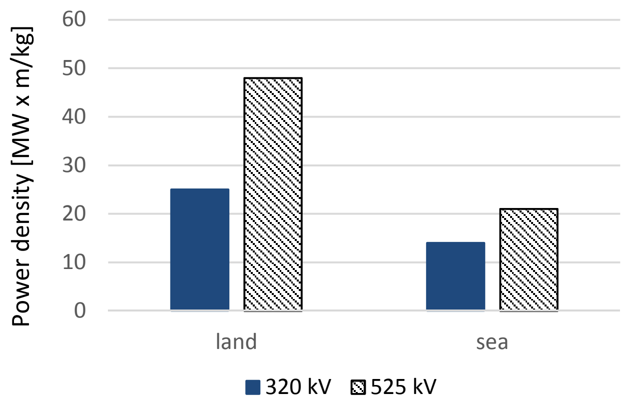

Figure 15: Power density comparison of a 320 kV extruded DC cable system with the 525 kV cable system. Comparison for 1.5 GW or less, 525 kV Al, 320 kV Cu.

CONCLUSIONS

A 525 kV extruded HVDC cable system is qualified according to Cigré Technical Brochure No. 496.

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

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