High-voltage XLPERFORMANCE cable technology

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Deregulation of the electricity supply markets and growing environmental awareness are creating exciting new markets for power transmission solutions based on extruded cable technology. At the same time, improvements on all fronts are extending the use of XLPE (cross-linked polyethylene) insulated cable systems up to 500 kV. Today's cable system solutions are competitive with overhead lines, while new manufacturing methods are enabling submarine cables with integrated optical fibers and flexible joints to be supplied in longer lengths than ever before. Further development of extruded insulation systems is also contributing to the success of recent ABB innovations, such as HVDC Light, Powerformer™, Dryformer™ and Windformer™.

1 400-kV XLPE cable with an insulation thickness of 28 mm

High-voltage cable systems rated 220 kV and above have become part of the very backbone of modern-day power transmission infrastructure. This importance carries with it, however, a special responsibility on the part of the suppliers to ensure that the systems exhibit the highest reliability and, because of the high electrical stresses at such voltage levels, that the cables and accessories are properly coordinated.

Qualification of 400-500 kV cable systems

The IEC emphasizes the importance of reliability and coordination of the cables and accessories by recommending that the performance of the *total system*, consisting of cable, joints and terminations, be demonstrated. The comprehensive test program, including a 'pre-qualification' test, is described in detail in the draft IEC 62067.

ABB qualified as a supplier of cable systems for the 400-kV voltage level in 1995 and is currently running a qualification test for systems at 500 kV.

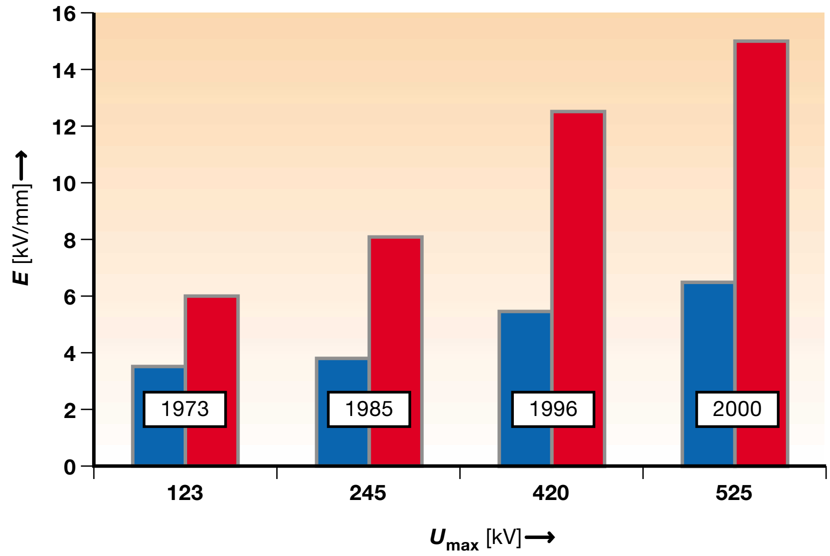
Quality, materials and manufacturing

ABB manufacturing sites for HV cables and accessories are ISO 9001 and 14001 certified, and consequently only certified suppliers are contracted to deliver essential materials. In the case of key insulation material for extra-high-voltage (EHV) cables, special quality assurance measures apply which form part of a Quality Assurance Agreement with the supplier. These measures, all of which are undertaken on the supplier's site, include:

- Selection of the base resin based on on-line cleanliness control
- Extra fine filtration of the base resin
- Extended cleanliness inspection of the intermediate and XLPE compounds
- A stringent cleanliness specification that includes contaminants from 50 µm upwards
- Improved clean-room procedures and a special EHV operation manual
- Special operator training

2 Design stresses of XLPE cables and year of introduction

Blue *Outer semiconductor*
Red *Inner semiconductor*
E *Electrical stress*
U_{max} *Voltage*



Complementing these measures at the material supplier's end are improved methods of materials handling in the cable factory and special efforts made to optimize the manufacturing process.

The XLPE (cross-linked polyethylene) cable core is produced on a dry curing manufacturing line. The cable insulation system, including the conducting layers, is extruded in a single process using a triplex extrusion cross head located, together with the three extruders for the insulating and conducting materials, in a clean-room.

Cleanliness is not the only criterion watched over during the extrusion process. Also monitored are:

- The interfaces, to ensure smoothness and a strong bond between the insulation and conducting layers.
- The homogeneity of the insulation (minimum internal stresses).

A cornerstone of ABB's overall commitment to reliability is numerical modeling of the manufacturing processes and the new application environments. This encompasses diverse areas, such as non-linear visco-elasticity in solid mechanics, diffusion of large molecules in semi-crystalline polymers, and non-Newtonian fluid mechanics.

Cable design

1 shows the 400-kV cable that was used in the qualification test. The cable's copper conductor, which has a cross-sectional area of 1600 mm^2, is divided into five segments to reduce skin effect losses. ABB uses segmented (Milliken) conductors made of stranded wires for cross-sections greater than 1000 mm^2. For cross-sections smaller than 1000 mm^2, the conductors are highly compacted to obtain a rounder, smoother surface.

The metallic screen consists of copper wires on a bedding of crepe paper to reduce the mechanical and thermal impact transferred to the insulation. The number of wires and the total cross-section depend on the short-circuit requirements of the network. Longitudinal water tightness is achieved by filling the gaps between the screen wires with swelling powder.

External protection against mechanical impact and corrosion is provided by a tough, extruded, laminated sheath made from HDPE (High Density Polyethylene). A bonded aluminum foil on the inside of the sheath stops water from diffusing into the cable.

The resulting lean, low-weight cable has several advantages: a greater length of cable can be wound onto any given drum; high eddy current losses in the cable sheath are avoided; the current-carrying capacity is optimized.

Possible oversheath options are:

- An extruded conductive layer for outer sheath measurements
- An extruded flame-retardant layer for extra safety in hazardous environments

Another option the cable design offers is space-resolved temperature monitoring with optical fibers. The fibers are contained in a stainless-steel tube of approximately the same size as a screen wire, which is integrated in the cable screen. Monitoring the temperature in this way enables the cable load to be optimized.

Insulation thickness

As 2 shows, the design stress of high-voltage XLPE cable increases with the voltage range. Already ten years ago a well-made HV XLPE cable could be expected to give several hundred hours of service at a conductor stress of 50 kV/mm [1]. Just a few years later field experience began to indicate that, since the lifetime exponent n increases with decreasing electrical stress, it was reasonable to expect a threshold stress not far below 50 kV/mm 3. In the meantime, HV XLPE cable technology, material quality, handling and manufacturing, have all been improved further.

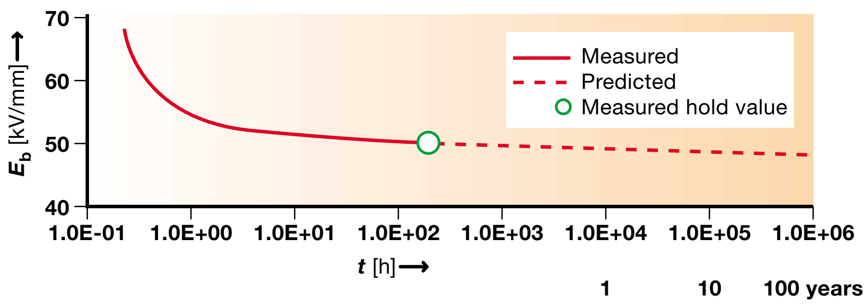
This experience, as well as tests on XLPE cables from ABB, have shown that test stresses of up to at least 40 kV/mm can routinely be used. Using higher stresses than this, while possibly improving the effectiveness of the test, has only a negligible effect on the lifetime. It can be concluded from this that the design stress for EHV XLPE cables could exceed 15 kV/mm in the near future.

Cable accessories

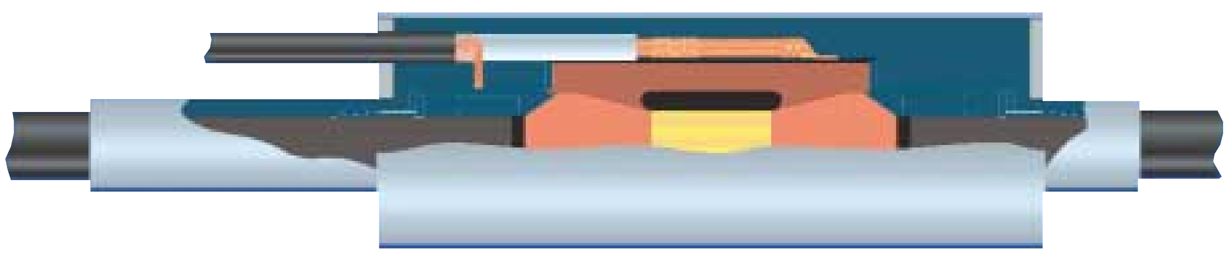
In the early 1990s ABB developed a prefabricated joint for EHV cables which is totally dry, ie with neither gaseous nor liquid materials, and maintenance-free. The main electrical parts can therefore be pre-tested in the factory, speeding up on-site installation and reducing the attendant risks 4.

The joint consists of an epoxy-resin insulation body with integrated field control electrode. 'High-voltage sealing' of the cable to the joint body is achieved by means of rubber stress cones with a deflector for integrated stress control. The stress cones are mechanically pre-stressed

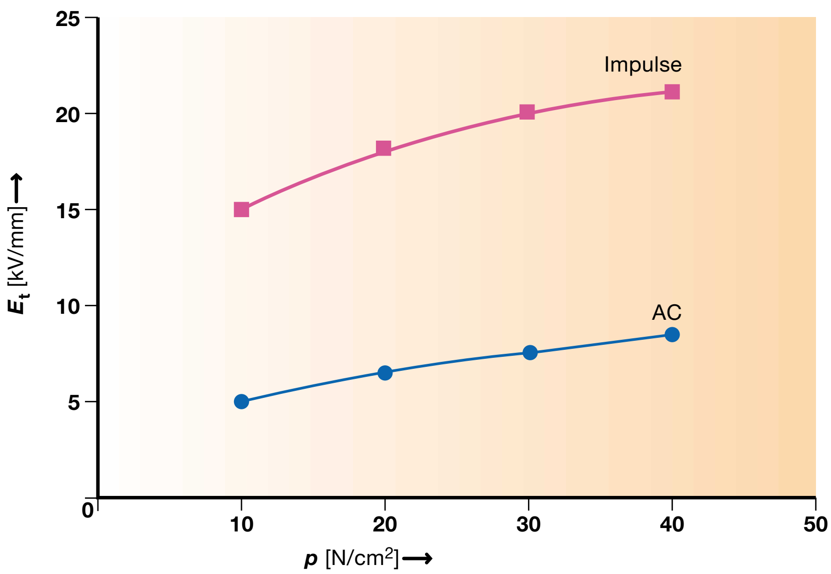
3 Lifetime curve for ABB XLPE cables; breakdown stress (*E*) versus time (*t*)



4 This prefabricated EHV cable joint, developed by ABB, contains neither gaseous nor liquid materials and is maintenance-free.



5 Breakdown strength (tangential, E_t) of the rubber-epoxy interface as a function of the interfacial pressure (p)



6 Temperature distribution inside the cable joint, calculated using the finite elements method, in air

$T_{ambient}$ 25 °C; cable temperature 95 °C; red 65 °C; blue 40 °C

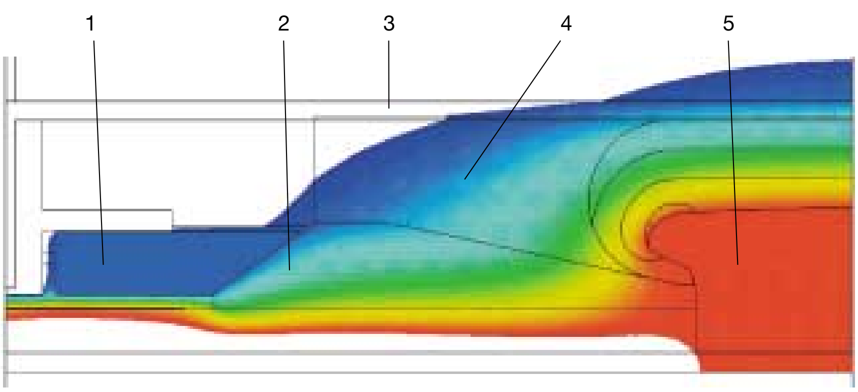
1 *Pressure device*

2 *Rubber stress cone*

3 *Joint housing*

4 *Joint body*

5 *Center electrode*



by a metal spring-device. This ensures a homogenous pressure distribution at all the electrical interfaces, irrespective of the thermal expansion of the cable or the stress cones themselves. The behavior of the joint has been verified by calculations carried out at ABB Corporate Research using the finite elements method. A certain pressure is necessary at the electrical interfaces if they are to withstand the high electrical stresses 5.

To obtain rules for a reliable electrical design, an experimental set-up capable of producing an almost purely tangential electrical field was devised and used to investigate the electrical interfaces. Further investigations were carried out to determine the temperature distribution inside the joint body 6. The joint also has an integrated capacitive PD sensor for on-site PD measurements and monitoring after installation.

The joint body has integrated sheath insulation to meet the requirements of the CIGRE recommendation contained in Electra 128, which requires it to withstand impulse voltages of 125 kV between the two joint sections and 63 kV to earth. This permits cross-bonding of the cable screen, which reduces the induced screen currents and losses in the AC cable system.

The complete cable system with joint, outdoor terminations and GIS terminations, fulfilled the requirements of the qualification test in every respect.

Testing of 400-kV and 500-kV cables

In the case of medium-voltage cables it is usual to think in terms of components.

Even if these come from different suppliers, they can be joined together and the system as a whole will still work. This is why limits are given for the electrical stresses in the construction requirements in IEC 60502.

HV and EHV cables and accessories, on the other hand, are designed as systems. No construction requirements exist for cables for these voltage levels, just the test requirements in IEC 60840 and the draft IEC 62067.

Qualification as per draft IEC 62067

The qualification of HV and EHV cable systems combines normal type-testing with a pre-qualification test. The aim of the latter test is to realistically stress the cable system by subjecting it not only to voltage stress but also the thermo-mechanical stress that occurs in service. An aging effect is obtained by increasing the test period to one year, compared with the 20 days for a normal type-test. The thermo-mechanical stress is simulated by running full-load cycles and using a longer cable than is usual for the type-test. In addition, the cable is laid in a way that is comparable with real-world applications.

The complete cable system – a 100-m long cable with all accessories – has a voltage of 1.7 U_o[1] applied to it for one year. During this time it experiences at least 180 load cycles with temperatures between 90–95 °C and ambient. Finally, cable samples are subjected to a lightning impulse voltage test.

7 Europe's first 400-kV XLPE cable system, at Altbach in Germany

Routine and on-site testing

Unlike the type-tests and pre-qualification tests, routine and on-site tests are carried out on parts that will be taken into operation after testing. The test stresses must therefore be chosen so that the components are not damaged. Draft IEC 62067 refers to a possible threshold of 30 kV/mm, but offers an extended test period to compensate for the lower test voltage (the minimum routine test voltage is 1.5 U_o, the maximum time 10 hours). For insulation systems (for which threshold limits are not a problem) the supplier may increase the test voltage and reduce the test period to 30 minutes.

[1] U_o = Rated design voltage between conductor and screen

Draft IEC 62067 recommends that a DC sheath test and/or AC test be carried out on the main insulation after the cables and accessories have been installed. If only the sheath test is carried out, the quality assurance measures during installation of the accessories may be substituted for the insulation test.

Partial discharge (PD) measurements can be carried out during the AC voltage test, but since the cables are routinely tested in the factory such measurements can be limited to the accessories installed in situ. Modern cable accessories have integrated sensors which allow PD measurement with the required sensitivity. The sensors can be linked to a monitoring system in order to gain further information about the in-service behavior of the accessories. Each sensor

8 400-kV cable system in a 6.3 km underground tunnel running through Berlin's city center

then sends its signal via an optical fiber and special coupling device to a processing unit for display and diagnostics.

A monitoring system of this kind is currently installed in a 400-kV XLPE cable system in Germany.

400-kV and 500-kV XLPE cable projects

ABB's first commercial order for the supply and installation of a 400-kV XLPE cable system in Europe came in 1993 from the German utility Neckarwerke. The cable was required to connect the main transformer to the gas-insulated switchgear for a new generation unit at the Altbach/Deidizau thermal power station. This cable features a longitudinal and radial watertight design with an 800 mm^2 aluminum conductor, a 150 mm^2 copper screen, and a laminated sheath made of aluminum foil and HDPE. Outdoor terminations were used at the transformer bay and GIS terminations for the connections to the switchgear. The 380-meters long cable circuit was installed in a channel with a separate tray for each single-core cable. Energization of the cable took place in August 1996 7.

In that year (1996) ABB also received an order from the public utility Bewag to supply and install a 400-kV XLPE cable system in a 6.3-km long underground tunnel in the center of Berlin. The ventilated tunnel runs at a depth of 25 to 35 meters below ground and has a diameter of 3 meters 8. The cable system, with a 1600 mm^2 segmented copper conductor, has a transmission capacity of 1100 MVA and forms part of a diagonal transmission link between the transmission grids west and east of the capital.

The cable is installed with the three phases arranged vertically, one above the other, on specially designed cable saddle supports 7.2 meters apart, with a short-circuit-proof spacer in the middle of each span. The cable route was divided into nine sections, each approximately 730 meters long. GIS terminations were installed at the two substations and the new ABB joint was used to interconnect the cable lengths. The laid cable consists of three main cross-bonded sections, with three minor sections within each main section.

During commissioning of the cable circuit, tests were performed with an AC voltage of 400 kV (1.73 U_0) and partial discharge measurements were carried out on all accessories. The cable circuit went into service in December 1998.

The Bewag utility awarded a second 400-kV XLPE cable contract to ABB at the end of 1998, this time for a 5.4-km long system, again in an underground tunnel. This cable circuit completes the diagonal link between the transmission grids west and east of Berlin, and was handed over to the customer in July 2000.

In May 1999 ABB received its first 500-kV XLPE cable order. The contract calls for two cable circuits almost 400 m in length to be installed in a hydropower station in China. The cables connect the transformers in the power station cavern to the gas-insulated switchgear located above ground. About 150 meters of the cable route will be in a vertical shaft. The cable is due to be delivered as soon as pre-qualification testing has ended. Installation is scheduled for 2001.

New submarine cable projects

In 1998 ABB was awarded the Channel Islands Electricity Grid Project, which will reinforce the power supply from France to Jersey and, for the first time, connect Guernsey to the European mainland grid. The submarine part of this project was completed in July 2000.

The main components delivered for the project were:

- Submarine cables between France and Jersey and between Jersey and Guernsey (approx 70 km)
- Underground cables on Jersey and Guernsey
- GIS substations
- New transformers and reactors

The system voltage is 90 kV. Although fluid-filled submarine cables were originally specified for this project, XLPE cables were finally chosen as being a technically and environmentally superior alternative.

The two submarine cables are of the same basic design, ie three-core, separate lead-sheathed, and with triple-extruded XLPE insulation. Each has a fiber optic cable with 24 fibers integrated in it for system communication and inter-tripping. The cables have double wire armor – ie, an inner layer of tensile armor and an outer, so-called rock armor - to protect them from damage that could be caused by tidal currents and fishing.

The cables have a diameter of approximately 250 mm and weigh about 85 kg/m in air.

Both cables were delivered by the factory in their full lengths, so no jointing was necessary on-site. This is made possible by a new vertical laying up machine that enables cables to be manufactured in any required length.

Also part of this project are separate armored submarine fiber optic cables, which were laid parallel to the power cables.

Because of the risks posed by fishing activities, the cables between Jersey and Guernsey and the fiber optic cables between Jersey and France were jetted into the seabed for extra protection.

Another new submarine cable project recently awarded to ABB is the Ma Wan and Kap Shui Mun Cable, which crosses a channel in Hong Kong. Due to the heavy traffic in this channel, it was decided to forgo conventional installation of the 132-kV and 11-kV systems, which would probably have disturbed shipping even if modern techniques were used. The problem is being solved by drilling under the sea bed and installing ducts through which the cables will be pulled. This has the extra advantage of allowing upgrades to be carried out in the future.

Separate control systems will be installed to monitor operation of the cable link, which will be completed early in 2002.

New cable contributes to recent ABB innovations

Several recent ABB innovations in the T&D field incorporate advanced HV cable technology: the HVDC Light concept, launched in 1997; the Powerformer™ generator, which was introduced in 1998; Dryformer™, a dry-type power transformer that went onto the market in 1999; and Windformer™, a new wind turbine generator designed to generate power offshore and in coastal areas and to transmit the power to the utility grid.

Powerformer,™ Dryformer™ and Windformer™

The market success of Powerformer™ [2], Dryformer™ [3] and Windformer™ [4] depends to some extent on the XLPE insulation being downsized yet still able to guarantee the required high voltage levels. Grounding and protecting the cables inside the machines, enabling the screen and outer jacket to be eliminated, also contribute to a leaner cable, and therefore to smaller machines.

The cable used in these innovations was developed with specific criteria in mind. For example, it had to meet the requirements of current carried by a low-loss conductor, designed to operate in an external magnetic field. Other design considerations were the high voltages and the goal of a completely circular and compact construction.

HVDC Light

High-voltage DC (HVDC) cables are employed for bulk power transportation over long distances, mainly underwater. The cable technology is based on paper insulation systems impregnated with highly viscous oil. While these cables have many technical advantages, the manufacturing process is slow and the end-product is mechanically sensitive. The industry has therefore been looking for a long time for an extruded HVDC cable of the kind used in AC systems.

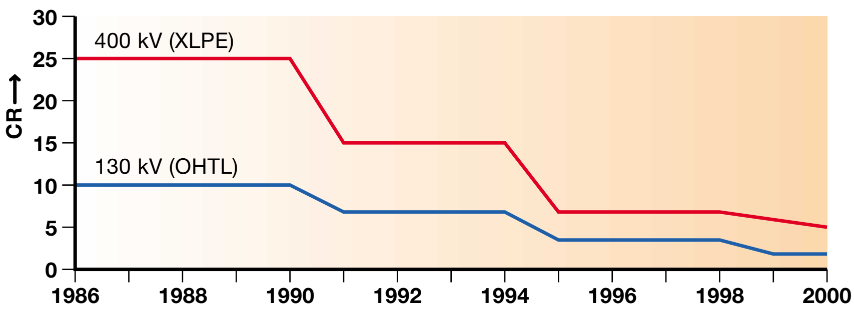
The difficulties encountered in developing such a cable have mainly concerned the space charge movements in the material. The high DC field forces space charges to move and accumulate, causing local increases in stress that eventually lead to breakdown. Besides good space charge properties, materials are required which exhibit high resistivity and high electric breakdown strength.

New types of DC accessories have also been developed. This work, which focused on the high-stress interface phenomena between the materials, has produced tape-molded joints as well as prefabricated joints adapted for extruded DC cable transmission. Another new development are prefabricated polymeric terminations featuring resistive control of the DC electrical field.

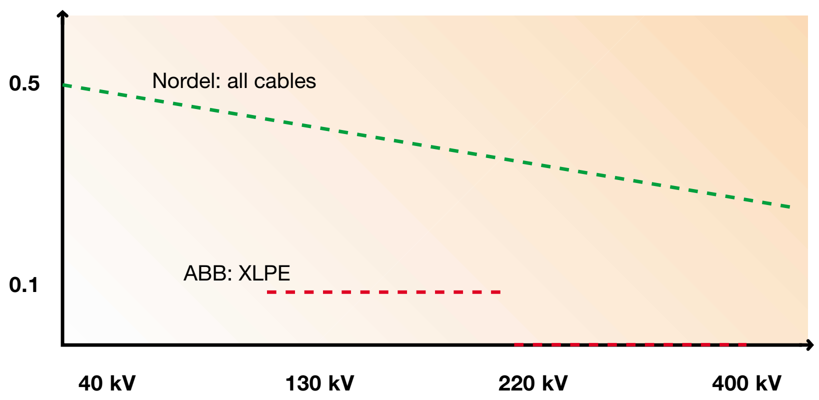
With HVDC Light [5], ABB has introduced to the market an extruded cable system, together with new transistor-based converters, that makes HVDC transmission competitive even at low power ratings. The first commercial system, a link rated 50 MW, was installed on the Swedish Island of Gotland, where it transmits power from a wind power plant to the town of Visby [6]. The latest project is the Directlink, rated 180 MVA at 80 kV, which transfers power between the states of New South Wales and Queensland in Australia.

While HVDC Light makes HVDC transmission viable for lower-rated links, extruded cable systems can, of course, be used for higher outputs. ABB currently offers cable systems rated to 150 kV for HVDC Light.

9 Comparison of cost ratios for XLPE cable systems and overhead transmission lines (OHTL)



10 Service failure rates of installed cables have been falling steadily.



Applications foreseen for HVDC Light include:

- Feeding of isolated loads
- Asynchronous grid connection
- Transmission of power from small generation units (eg, wind power plants)
- DC grids
- HVDC deepwater installations located away from the interconnections

Deregulation – changing the rules

In today's deregulated electricity markets, the rules that used to govern generation, transmission and distribution have changed for both the power utilities and suppliers. Suddenly, it is the customer who is in the spotlight. Accordingly, the market has to listen more to public opinion, and there is a strong possibility that this will include a call for a less 'visible' T&D infrastructure.

All the actors in this new market are having to reduce their costs and at the same time guarantee high reliability for the transmission and distribution systems.

A likely scenario is that new cable interconnections will be built and operational margins will be utilized more fully in order to get maximum technical and economical benefit from the electrical network. More 'intelligent' networks will be built, possibly in cooperation with fiber network companies.

The power utilities are also outsourcing non-core activities and becoming electricity traders rather than technicians or administrators. Electrical system solutions and turnkey supplies will become more attractive for the new customers they have in focus.

Extruded cable systems have a major part to play in this new, competitive environment, especially when it comes to replacing overhead lines with underground cables.

XLPE cable systems costs have decreased during the last decade and are likely to fall even further. As their costs have gone down, the performance of XLPE cables has increased enormously. The new message is therefore that XLPE cable systems are able to compete with overhead lines, technically, environmentally and commercially. This is particularly true in the voltage range of 12–170 kV 9.

Extruded insulation – performance and improvements

The service failure rates of installed XLPE cables have continued to decrease over the years. 10 compares the failure rates given by Nordel, a society set up for the exchange of information between members of the Nordic electricity market, and ABB data. In the Nordel statistics all cable ratings are included, whereas the ABB data refer only to XLPE cables > 100 kV.

The well-established trend towards a smaller insulation thickness will continue, resulting in a leaner cable 11 with many advantages, among them longer dispatch lengths, fewer joints, easier installation, and reduced thermal contraction/expansion of the insulating material.

Experience accumulated during EHV XLPE cable system development, improvements made in materials and processes, and the excellent service record of XLPE, all indicate that the thickness of XLPE cable insulation will very likely be reduced to 10–12 mm for 132-kV cable systems in the near future. This will, in turn, place the XLPE cable systems versus overhead line transmission scenario in a new light, with a cost ratio of 1:1 being approached for the new distribution class of 50–170 kV. (It is worth noting that a lifetime cost ratio of between 1:1 and 1:1.5 can be obtained for voltages between 50–245 kV.)

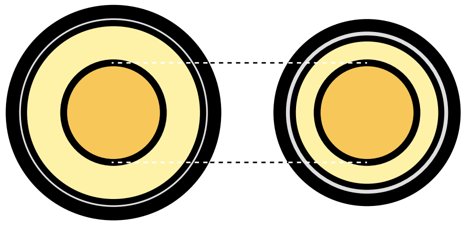
Underground cables versus overhead lines

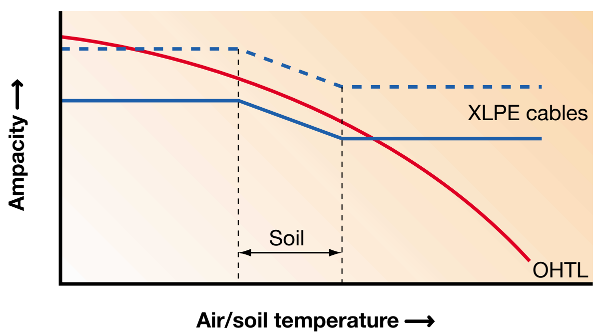
There are, of course, many operational, security, environmental and economic parameters that distinguish XLPE cable systems from overhead lines. For the new distribution class of XLPE cable systems (ie, 50–170 kV), the reduced cost ratio and environmental and reliability benefits are the most obvious and important considerations. Due to their larger cross-sectional areas, cables usually exhibit fewer losses per MVA than comparable overhead lines. A summary of the benefits of XLPE cable systems is given in the *Table*.

The ratings of the overhead lines are largely dictated by the high winter loads, which include a lot of electrical heating equipment. During hot summer days the overhead line carries some 50% less electricity than in winter, making them less attractive if load profiles have to be smoothed out in the future. In areas with a lot air-conditioning units, for example, the benefits of XLPE underground cables make them an obvious 'first choice' 12.

Underground transmission lines also have a better overload capacity for periods

11 Standard XLPE cable (left) and the new generation of lean XLPE cables





12 Rating of overhead line (OHTL) versus underground XLPE cable. The dashed line indicates that higher powers could be transmitted if the daily load cycle profile is taken into account.

Table: Benefits of underground transmission lines

Environment	*Grid security*	*Economy*	*Operation*
No visual impact	Not effected by wind, snow, ice, fog, etc	Less maintenance	Higher availability, fewer faults
Low/no electromagnetic fields	Nothing can be stolen	Minimum investment for lake/river crossings	Usually lower losses/MVA
High level of personnel safety, low risk of flashover in air		Land use minimized	Higher short-time overload capacity
Better working conditions		Value of land/buildings unaffected	

of time shorter than 60–90 minutes due to the high thermal mass of the surrounding soil.

There are several other factors that speak for installing an HV XLPE cable system:

- Civil works contractors have also been re-organizing their operations and have reduced costs.
- Infrastructure programs for broadband fiber solutions are in place today.
- The installation of optical fibers alongside power cables is a common and well-established practice.

Tomorrow's electrical infrastructure – here now

Extruded cable systems are available as total solutions, with a 'cradle to grave' supplier commitment. Such systems are turnkey solutions in the commercial as well as the technical sense. They could start with the permit application, continue with the removal of the overhead lines and the supply and installation of the cable system, and end with the environmentally friendly disposal of the old equipment.

Complete cable system solutions can also be seen as intelligent combinations of monitoring equipment, converters, load sharing devices, series and/or shunt compensation devices. Financing, too, can be arranged; here, leasing and a new type of availability guarantee could resolve several commercial uncertainties.

Together, these 'thumbnail' sketches of the future add up to a new customer-value-based market. Extruded insulated cable system solutions are destined to play a key role in this evolving market by meeting not only the transmission and distribution network requirements of today but also those of tomorrow.

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