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DC extruded Cable System design and its main characteristics

Laurent **BENARD ;** Prysmian câbles et systèmes, (France),
laurent.benard@prysmiangroup.com,
Mohamed **MAMMERI ;** Sileccable, (France),
mohamed.mammeri@sileccable.com
Pierre **MIREBEAU** ; Nexans, (France),
pierre.mirebeau@nexans.com

ABSTRACT

Underground HVDC links are considered as a solution to answer to the demand for countries interconnection associated to the difficult acceptance of overhead lines. HVDC is compulsory when the interconnected networks are unsynchronised. When the interconnected networks are synchronous, cable system transmission losses encountered in AC are reduced by working in DC. For long length HVDC can be the best choice.

In the present paper the authors present case studies of long underground AC and DC links.

DC insulation resistance and space charge properties are important for the assessment of the electric field in the insulation and consequently on the cable system design.

KEYWORDS

Space charge, XLPE, VSC.

AUTHOR NAMES & AFFILIATIONS

Laurent BENARD ; Prysmian câbles et systèmes, (France),
laurent.benard@prysmiangroup.com,
Mohamed MAMMERI ; Sileccable, (France),
mohamed.mammeri@sileccable.com
Pierre MIREBEAU; Nexans, (France),
pierre.mirebeau@nexans.com

CABLE SYSTEM DESIGN, AC VERSUS DC

A cable system consists in

- Cables (land – submarine)
- Joints (land – factory – repair)
- Terminations (outdoor – GIS)

Differences between submarine and land links lie in one hand in the mode of transportation and laying of the cable and in the other hand in the way to repair the link.

For submarine links, it is easy to transport long lengths of cable by using a ship but in case of breakdown or damage repair of the link is difficult. These aspects have led to the development of two dedicated joints: the factory joint, in order to increase as much as possible the cable length in relation with ship capabilities, and the repair joint in order to yield the restoration of the link with reliability.

For land links, the transportation of long length of cable is difficult but installation jointing and repair of the link are easy. For both applications, the same joint can be used.

The main interest of AC network compared to DC network is the possibility to change easily the voltage level, in particular in case of high voltage, by using power transformers and then allows decreasing the losses for the same transmitted power by increasing the voltage.

In HVDC there is no reactive power and no compensation is needed. The electrical losses are smaller (no skin effect). For these reasons, HVDC is used for long-distance point-to-point transmissions (submarine links, interconnection between countries...). Another application of HVDC systems is the transmission between two unsynchronised AC networks or the connection to the network of asynchronous generators (wind farms...).

Shunt compensation for AC links

Power cables are cylindrical condensers when considering phase and screen conductors.

Under AC voltage, a reactive power is introduced in the link which needs to be compensated by the utilisation of shunt reactors at the terminations. In case of very long links, terminations are introduced in the course of the link as shown in Fig. 1.

Fig.1: Shunt compensation at terminations

Maximum active power transmission is attained when the same reactive power is evacuated at both ends of the link.

The voltage and current are as described in Fig. 2 [1].

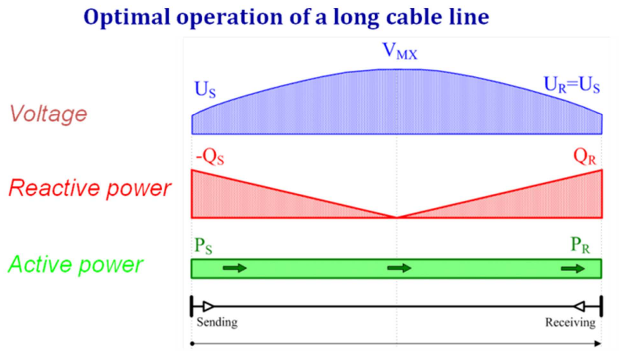


Fig 2: P, Q and V along the link in case of both ends shunt compensation

Converter technology for DC links

DC Transmission requires convertors stations at both ends to convert AC to DC at sending point, and DC to AC at receiving end (Fig 3).

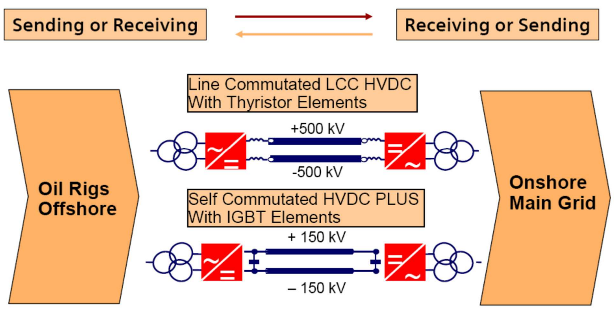


Fig. 3: DC link diagram.

There are two main Technologies for DC Transmission.

Line Commutated Converter (LCC)

A LCC has the feature of changing voltage polarity of the cable system by means of a control action.

LCC uses Thyristors. The current flows in one direction only. Therefore when the power flow is reversed, the polarity on the HVDC cable system is reversed.

LCC can be used up to very high powers (800kV, 5000MW) [2], are rugged and have low losses. Such a technology requires site area relatively large because of the need of switchable harmonics filters.

Voltage Source Converter (VSC)

A VSC permits to reverse power flow without changing the voltage polarity of the cable system.

In service since 1997, Transistor based VSC gives more operating flexibility to network operators. Currently used up 320 kV DC rated voltage.

Fig. 4 shows the generation losses of VSC and LCC [3].

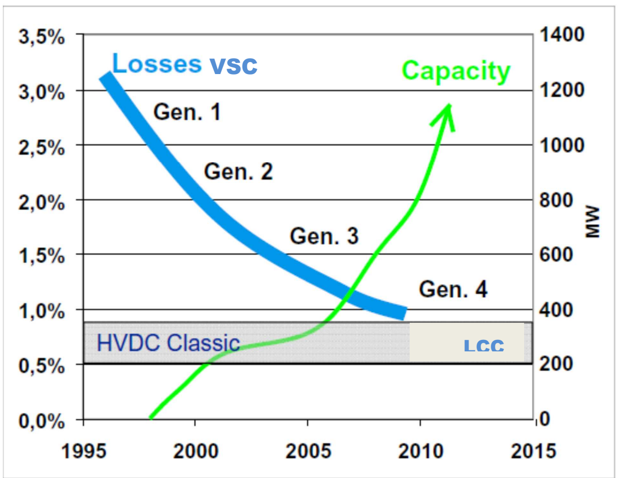


Fig. 4: Losses of VSC and LCC

To conclude, the usual range of application of AC and DC cable systems is illustrated in Fig. 5.

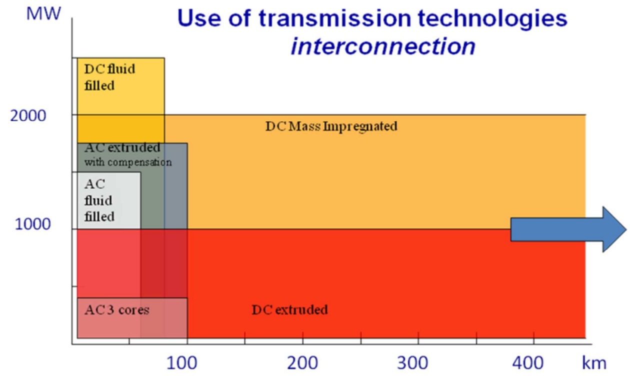


Fig. 5: Application of AC and DC cable systems.

Global losses of the links

In DC the main losses are the sum of generator losses, joule effect losses, and voltage drop.

In AC the main losses are the shunt reactor losses, the voltage drop and the Joule effect.

A global assessment of losses is given in ref [4].

EXAMPLES OF LONG LENGTH AC AND DC CABLE SYSTEMS

AC links

XLPE is the main material used for the insulation of AC cables thanks to the combination of notable properties:

- Reduced permittivity as compared to lapped insulation systems;
- High dielectric strength;
- Slight dielectric loss factor;
- Good thermo-mechanical properties;
- Easy to transform.

XLPE Land cable system 500MW 225kV PACA

The reinforcement of the unique 400kV Overhead Line to supply the South East of France area is made using 225kV underground cables (Fig. 6) [5].

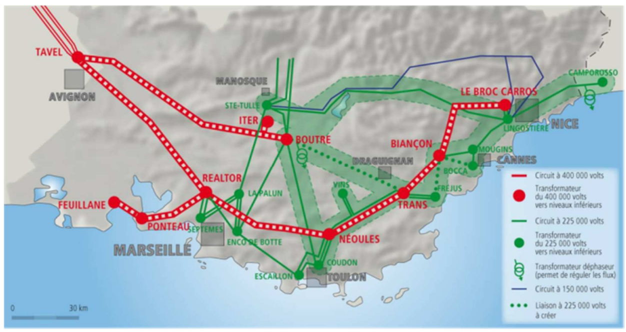


Fig.6: Map of the underground 225kV links (green) and OHL (red)

There are 3 links:

- Boutre-Trans: 65 km
- Biançon-Fréjus: 25 km
- Biançon-La Bocca: 20 km

The total number of joints is 3x68, drums are up to 50 T (≈1400 m)

Fig. 7: 2500mm² enamelled copper 225 kV XLPE Cable

The conductor cross sections are 2000 and 2500mm² depending on the thermal environment.

2500mm² cable has a diameter ≈ 130 mm, weight ≈ 33 kg/m.

There is a shunt reactor at each substation for a total of 160MVAR.

DC links

Mass Impregnated 400MW +/- 250kV Cometa link.

The Cometa link is between Spain and Mallorca (Fig. 8) [6]. The design of the cables deployed in the Cometa Project has been optimised to be able to install the whole length (250km) in one laying campaign (7000T). The HVDC cables have a copper cross section of 750 mm2. A design with a single layer of flat armour wires was chosen for the shallow part of the route up to 200 m water depth close to both shore ends. For the deeper water middle section (Fig.9), a double flat wire armour layer was used.

Fig. 8: Cometa link between Spain and Mallorca

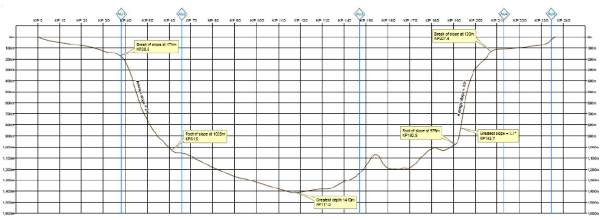


Fig.9: Cable route profile (50% is below 1000m, max depth 1485m)

The next figure shows the cross section of the deep water cable.

Fig.10: 750 mm² Cu +/- 250 kV Mass Impregnated cable

There is a LCC converter station at each end of the link.

XLPE 400MW +/-200kV Trans Bay Cable

The Trans Bay Cable Project (TBC Project) is a 400 MW, ±200 kV, submarine-based, point-to-point, DC transmission system which transmits power from the generation resource-rich area of Pittsburg, California to the City and County of San Francisco (Fig. 11) [7].

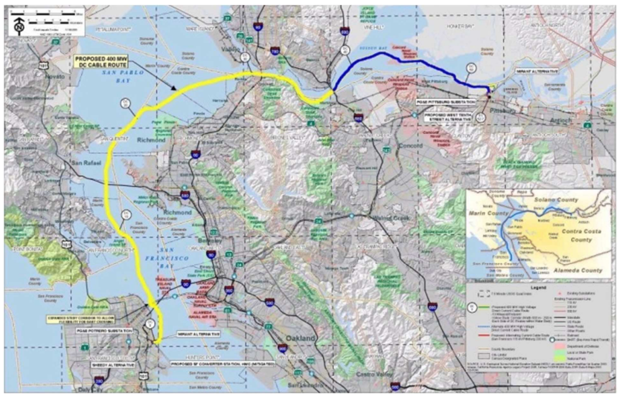


Fig 11: Submarine cable installation route (blue for shallow waters and yellow for deep waters)

A basic scheme of the link is reported in Fig.12.

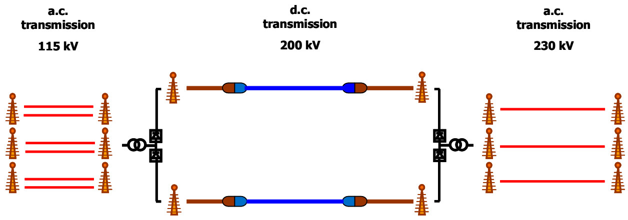


Fig. 12: Basic layout of the whole connection

The most significant cable part of the TBC Project is the ±200 kV DC submarine cable. The power rating of the connection is 400 MW, which is considered as increased by 5% at sending point thus giving a nominal rated current of 1050 A.

Fig. 13: 1100 mm² Cu +/- 200 kV XLPE cable

XLPE 2x 1000MW +/- 320kV France/Spain Interconnection

The project is called INELFE and is meant to transmit 2000 MW nominal power 64 km across the Pyrenees between Spain and France. The system is composed of a long double-bipole having a total cable quantity of 256 km. Figure 9 here below gives an overview of the connection and its electrical layout [7].

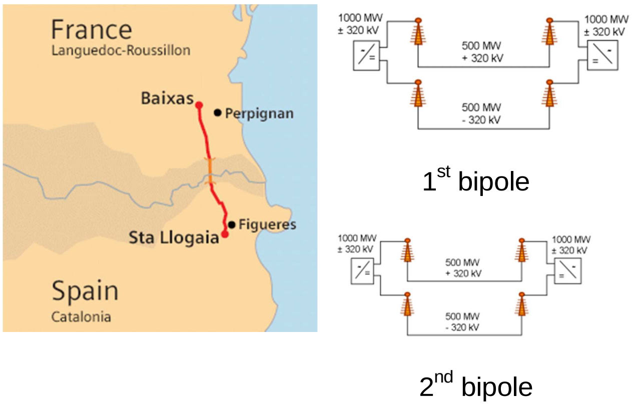


Fig 14: INELFE layout and scheme

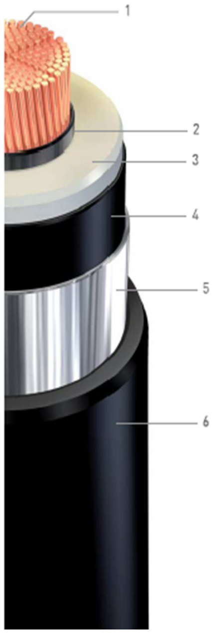
Cables are 320 kV rated, with 2500 mm2 copper conductor, extruded insulation, longitudinally welded aluminium sheath as radial water barrier and plastic outer sheath.

Fig. 15: 2500 mm² Cu +/- 320 kV XLPE cable

Cables and accessories have been subjected to long term and short term testing, in accordance with Customer requirements, derived from Cigré Technical Brochure 219.

EXTRUDED HVDC CABLE SYSTEM

Main characteristics of DC cables



1- **Conductor**: Main current carrying medium for load transfer. Its cross section masters the losses.

2- **Inner semi-conducting conductor screen:** Provides smooth interface between conductor and XLPE insulation.

3- **Cross-linked polyethylene (XLPE):** Main insulating medium for the high voltage. It ensures electrical separation between conductor and environment

4- **Outer semi-conducting core screen:** Ensures that radial electrical field is confined into the cable. Provides smooth interface between XLPE insulation and metal screen.

5- **Metal screen:** Ensures radial electric field. Carries the earth fault current Offers mechanical protection Prevents radial moisture ingress

6- **Outer Sheath:** Protects the inner layers from corrosion and other environmental attacks**.** Depending on the installation type, a conductive coating may be applied on the oversheath to enable operator to perform sheath integrity test

The main difference between DC vs AC design is the use of dedicated compounds not only for insulation but also for semi-conducting screens.

Electric stress in HVDC cables and accessories

Using polymers as insulation for HVDC cable and accessories is a challenge for a number of researchers and manufacturers due to some advantages that polymeric insulation can offer in comparison to traditional laminated. Dielectric time constant and space charges formation under DC stress is certainly the major concern for such a material. Indeed, the space charges build up modifies the electric field distribution inside the insulation and leads to local overstresses which may be detrimental to long-run ability.

Resistive field distribution

When a DC voltage V is applied across the cable insulation, in the first period, the stress distribution is capacitive. But after some time constant ($\tau=\rho.\varepsilon$) under static conditions the charges can move and the stress distribution becomes resistive [8].

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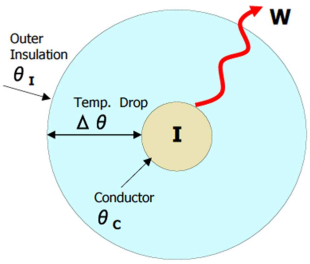
The resistive distribution is led by the insulation conductivity σ which varies as a function of the stress E and temperature θ:

$$\sigma = \sigma_0 \, {}^{\alpha}_{0}{}^{+\beta E}$$

Where stress is higher, insulation conductivity is better (lower resistance) and the charges are moved away from the high stress zone to the low one.



When a current I flows in the conductor, Joule losses generate heat (W). The heat crosses the insulation, thus causing a temperature drop Δθ across the insulation. The inner part of the insulation is hotter than the external one, therefore the conductivity is further increase by the temperature effect, and consequently the charges are further moved away from the inner to the outer insulation layer. Depending on stresses and temperatures, there can be a stress inversion, with outer stress on insulation higher than the inner one (Fig.16):

$$E_e > E_i$$

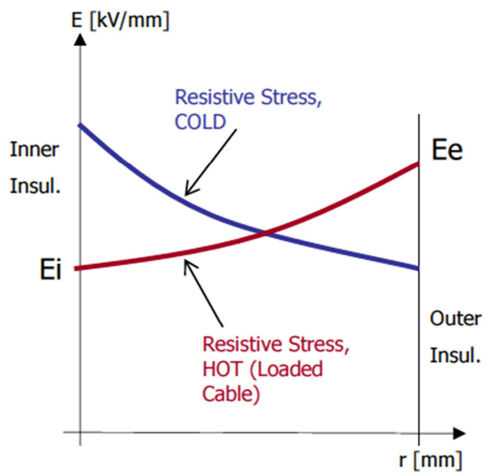


Fig.16: Resistive field distribution with / without temperature gradient

Space charge field enhancement

It is known the space charge can be electronic or ionic in nature. These charges can be injected from the semi-conducting shield used in DC power cable geometry or can be formed by residues dissociation under the action of the electric field. Even after degassing, the insulation may contain a non-negligible amount of by-products and their distribution might be inhomogeneous across the insulating material promoting net space charge build up.

Space charge is partially fixed inside the bulk of insulation material by traps. In polymeric insulation two kinds of traps must be considered:

⇨ Physical traps such as "Conformational Disorder" 10^{27}-10^{28} /m³

⇨ Chemical traps (residues, antioxidants, by products…) 10^{24}-10^{25} /m³

Charge Density measured is in the range of 1 to 10 C /m³ approximately [9].

It has been found useful to combine the spatial distribution of space charge to the measurement of a parameter known as Field enhancement factor (FEF). FEF is defined as a ratio of the field at a given location as compared to the Laplace field (i.e. field without space charge).

A material with FEF=1 is the preferred choice for DC application. In case of heterocharges accumulation close to the electrode, the electric field will be higher than the Laplace field resulting in FEF values > 1.

An example of Space charge profiles realised during poling indicates that hetero-space charge is accumulated at the anode as well as at the cathode Fig.17 [9].

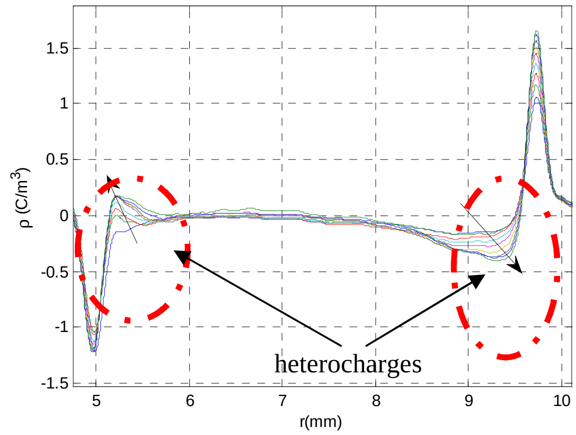


Fig. 17: Voltage-on space charge density in model cable poled at 25 kV/mm at 20℃

Similar to cable insulation DC insulation resistance (ρ) properties and the space charge properties must be explored on the main insulating material of the pre-moulded accessories. Fig. 18 shows an example of measurement results. The tests are conducted as a function of electric field. The samples are submitted to 8 hours withstand poling [10].

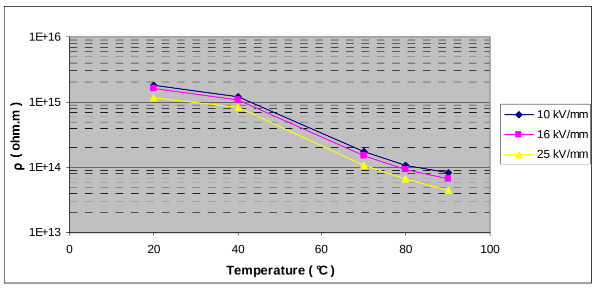


Fig. 18: DC resistance properties of EPDM

The electric field distribution in the insulating components of the accessory varies depending on the shape of electrode and the deflector that control the electric field as well as the electric field and temperature Figure 19 plots the electric field distribution obtained by finite element calculation at a pre moulded joint. On a 2500 mm² conductor and insulation thickness of 21.5 mm for U_0 = 320 kV.

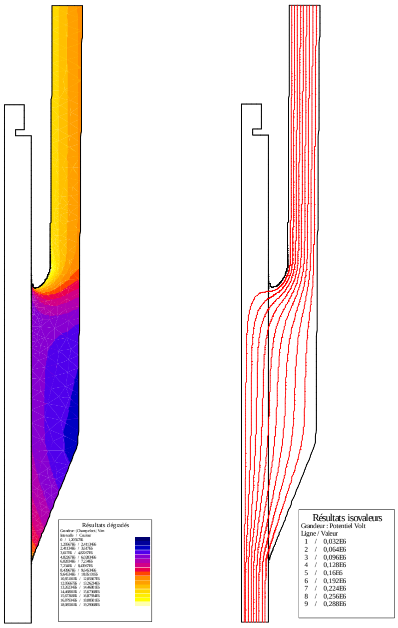


Fig.19 : Electric field distribution in pre moulded joint.

In addition, at each interface where there is a discontinuity of electrical properties (resistivity, permittivity, time constant...) there is a layer of space charges (Maxwell – Wagner effect) which affects the field distribution.

Rating

The dimensioning of the conductor cross section of HVDC cables takes into account two limiting parameters:

1. The rated maximum conductor temperature
2. The rated maximum Δθ across the insulation.

In cold environmental condition, the parameter 2 prevails and the maximum conductor temperature may be never reached.

In the case of warm environment, the parameter 1 prevails and the maximum temperature gradient across the insulation may be never reached.

These 2 parameters must be also considered when designing the overload conditions. That impacts the way the HVDC cable systems can be used when connected to a generation plant where there is no redundancy.

CONCLUSION

The increasing use of VSC technology where the power flow reversal occurs without changing polarity of the cable encourages the use of synthetic insulated cables and both long submarine and underground links are being considered and actively implemented.

The experience of Extruded HVDC cables at transmission voltages is recent (10 years) as compared MI insulation (60 years) and HVAC XLPE (45 years).

There is still a large knowledge to build up specially dealing with the dynamic of space charge under voltage and different temperature profiles over a long period, and the assessment of ageing mechanisms.

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